Proceedings of a Multidisciplinary Symposium on Saanich Inlet, 2nd February, 1983

S. K. Juniper and R. O. Brinkhurst, editors

Institute of Ocean Sciences
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Rapport technique canadien sur l'hydrographie et les sciences océaniques

Ces rapports contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles mais que l'on ne trouve pas normalement dans les revues scientifiques. Le sujet est généralement rattaché aux programmes et intérêts du service des Sciences et Levés océaniques (SLO) du ministère des Pêches et des Océans.

Les rapports techniques peuvent être considérés comme des publications à part entière. Le titre exact figure au-dessus du résumé du chaque rapport. Les résumés des rapports seront publiés dans la revue Résumés des sciences aquatiques et halieutiques et les titres figureront dans l'index annuel des publications scientifiques et techniques du Ministère.

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Les établissements des Sciences et Levés océaniques dans les régions et à l'administration centrale ont cessé de publier leurs diverses séries de rapports depuis décembre 1981. Vous trouverez dans l'index des publications du volume 38 du *Journal canadien des sciences halieutiques et aquatiques*, la liste de ces publications ainsi que le dernier numéro paru dans chaque catégorie. La nouvelle série a commencé avec la publication du Rapport n° 1 en janvier 1982.

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PROCEEDINGS OF A MULTIDISCIPLINARY SYMPOSIUM ON SAANICH INLET, 2 FEBRUARY 1983.

CONTENTS

Introduction - S.K. Juniper and R.O. Brinkhurst 1

I. Physical, Geochemical and Microbiological Processes in Saanich Inlet.

I.1 Overview
- S.K. Juniper 5

I.2 Deep Water Renewal in Saanich Inlet
- D.J. Stucchi and L.F. Giovando 7

I.3 The Oxic/Anoxic Interface in Saanich Inlet
- J.J. Anderson 17

I.4 Chemistry and Microbiology of Dissolved Gases in Saanich Inlet
- J.A. Baross. M.D. Lilley and M. de Angelis 25

I.5 Factors Controlling the Porewater Distribution of Carbon and Sulfur Species in Saanich Inlet
- A.H. Devol 27

I.6 Time series of Mercury in Saanich Inlet
- X. Lu, W.K. Johnson and C.S. Wong 37

I.7 Testing of New Oceanographic Instruments in Saanich Inlet
- D.M. Farmer 41

CONTENTS cont'd

II. Planktonic Processing of Carbon and Nitrogen in Saanich Inlet

II.1 Overview
- F.A. Whitney 43

II.2 Carbon Cycling in the Photic Zone of Saanich Inlet
- F.A. Whitney and C.S. Wong 45

II.3 Role of Zooplankton Fecal Pellets in the Vertical Transport of Organic Matter in Saanich Inlet
- K. Iseki and C.S. Wong 51

II.4 Nitrogen and the Biology of Zooplankton in Saanich Inlet
- L.A. Hobson 57

II.5 The Biological Front at the Mouth of Saanich Inlet
- T.R. Parsons 59

III. The Fauna of Saanich Inlet

III.1 Overview
- V.L. Tunnicliffe 61

III.2 Distribution and Respiration of a Low O_2 Tolerant Crab in Saanich Inlet
- B. Burd 67

CONTENTS cont'd

III.3 Seasonal and Vertical Distribution of Medusae, Siphonophores and Ctenophores in Saanich Inlet
- C.E. Mills 77

III.4 Submersible Observations of Plankton Distribution in Saanich Inlet.
- G.O. Mackie 81

III.5 Underwater Birdwatching
- W.C. Austin 83

IV. Provisional Bibliography of Oceanographic Information for Saanich Inlet.
- L.F. Giovando 91

V. List of Symposium Participants 103

ABSTRACT

Juniper, S.K. and R.O. Brinkhurst (eds). 1984. Proceedings of a Multidisciplinary Symposium on Saanich Inlet, 2nd February, 1983. Can. Tech. Rep. Hydrogr. Ocean Sci.: No. 38: 104 pp.

The papers in this volume describe some of the unique physical, geochemical and biological aspects of Saanich Inlet, a fjord on southeastern Vancouver Island. Various papers reveal how restricted deep water renewal profoundly affects the geochemistry and biology of Saanich Inlet through intermittent periods of anoxia.

key words: Fjords, anoxia, geochemistry, submersibles, fjord biology.

RÉSUMÉ

Juniper, S.K. and R.O. Brinkhurst (eds). 1984. Proceedings of a Multidisciplinary Symposium on Saanich Inlet, 2nd February, 1983. Can. Tech. Rep. Hydrogr. Ocean Sci.: No. 38: 104 pp.

Les diverses présentations continues dans ce volume dépeignent l'aspect trés particulier de l'anse de Saanich tant au point de vue physique que géochimique et biologique. L'anse de Saanich est un fjord situé au sud - est de l'île de Vancouver. Plusieurs de ces exposés révélent que la géochimie et la biologie de l'anse de Saanich se trouvent profondément affectiés par d'intermittentes périodes d'anoxie dues à la limitation du renouvellement des equx profondes.

mots clé: Fjords, anoxie, géochimie, submersibles, biologie des fjords.

INTRODUCTION

S.K. Juniper and R.O. Brinkhurst

The papers in this volume were presented at a symposium held at the Institute of Ocean Sciences, on 2 February, 1983. The symposium was organized to provide an opportunity for researchers who have worked in Saanich Inlet to meet and exchange information. Most oceanographic disciplines were represented in the program, providing participants and readers of this volume with an excellent overview of the unique biological, geochemical and physical characteristics of Saanich Inlet.

Saanich Inlet is a 24 km long fjord-like embayment located at the southeastern end of Vancouver Island. The inlet has a maximum depth of 228 m rising to a sill at the mouth with a depth of 75 m. The lack of significant freshwater discharge, the presence of the sill, and the narrow and deep morphology of the basin result in restricted water circulation. For much of the year the bottom waters of the inlet are anoxic. Flushing of the anoxic water can occur in the autumn and winter when dense, oxygenated water intrudes over the sill. It should be emphasized that this flushing is not a regular annual event in Saanich Inlet. Observations over the last two decades indicate that there are years when the anoxia is not relieved at all, and there is some evidence that intruding deep water occasionally causes an upward displacement of the anoxic layer rather than dispersing it. Deep water renewal in Saanich Inlet appears to be sufficiently unpredictable to attract the attention of physical oceanographers for some time.

THE PHENOMENON OF ANOXIA IN SAANICH INLET

The majority of papers at the symposium dealt directly with the development or effects of anoxia in Saanich Inlet. What follows is a simplified overview of the anoxia drawn from these papers and other published work on Saanich Inlet. This will aid readers in relating the physical, chemical and biological aspects of this phenomenon.

The anoxic "cycle" in Saanich Inlet can be seen as a sequence of events

that is fueled by phytoplankton growth. Fecal pellet production by grazing zooplankton results in the sedimentation of a substantial portion of the primary production. During periods of minimal deep water circulation, decomposition of this material in the sediments rapidly consumes available dissolved oxygen and anoxic conditions soon prevail in the bottom waters. This condition can be abated later in the year by intrusions of oxygenated water. As anoxia develops, the interface between anaerobic and aerobic processes migrates upward from the sediments into the water column. Microbiological and diagenic processes in the sediments and bottom waters shift entirely to anaerobic pathways, and an assemblage of chemosynthetic bacteria develops at the oxic/anoxic interface. The duration of the anoxia precludes the existence of a benthic fauna in the basin of Saanich Inlet and the oxic/anoxic interface acts as a barrier to downward migration of zooplankton

ANOXIC FJORDS IN BRITISH COLUMBIA

Saanich Inlet is one of a number of fjords along the British Columbia coast that show varying degrees of anoxia. These range from Howe Sound, which undergoes occasional anoxic events every few years to intermittently anoxic Saanich Inlet and several permanently anoxic fjords. The permanently anoxic fjords are:

a) Nitinat Lake (Vancouver Island) and Hidden Basin (Nelson Island) - These have shallow restricted entrances and are anoxic except for a surface layer.

b) Sakinaw Lake (Sechelt Peninsula) - This brackish lake has a sea level sill and receives occasional influxes of seawater at extreme high tides. The lower depths of this lake are anoxic.

c) Powell Lake (near Powell River town site) - This is an old fjord which has been cut off from the sea for around 7,000 years. It contains 200 m of anoxic saltwater overlain by 158 m of freshwater (T. Pederson. pers. comm.).

Editors' Note:

We have separated the papers into three sections. The first two sections are "process oriented" and provide some interesting examples of coupling between physical, geochemical and ecological processes, primarily in relation to the phenomenon of anoxia in Saanich Inlet. The papers in the third section are concerned with the distribution of the plankton and fjord-wall fauna in Saanich Inlet. The anoxia figures prominently here as well, for it profoundly affects the distribution of most organisms that are found in the deeper waters. Each of the sections is preceded by a brief overview which summarizes and relates the papers that follow. These give the reader an appreciation of the scope of recent research in Saanich Inlet, and the common threads that link the many disciplines represented here.

The fourth section consists of a bibliography of published and unpublished information on Saanich Inlet.

I. PHYSICAL, GEOCHEMICAL AND MICROBIOLOGICAL PROCESSES IN SAANICH INLET

I.1 OVERVIEW

S.K. Juniper

The papers in this section illustrate the influence of restricted water circulation on microbiological and geochemical processes in Saanich Inlet. Stucchi and Giovando point out that there is an annual cycle of renewal in the upper 100 m but at 200 m depth renewal is sporadic. As a result, for much of the year a vertical profile of the water column in Saanich Inlet consists of three major zones, defined by redox conditions: the upper oxic zone, the oxic-anoxic interface and the anoxic bottom waters.

The upper zone is characterized by photosynthesis, aerobic decomposition processes, exchange at the air-sea interface and formation and downward flux of particulates. The paper by Baross et al. reveals that even within this zone there exist anaerobic microniches which produce measurable concentrations of reduced gases. The lack of vertical mixing in Saanich Inlet causes the downward flux of particulates to exceed resuspension to a greater degree than in most coastal waters. This "washout" effect is illustrated in the paper by Lu et al. They report that the total mercury concentration in the upper waters of Saanich Inlet is the lowest yet measured in seawater. They suggest that this is because the rate at which mercury becomes affiliated with particulates and sedimented out of the upper zone is similar to the rate at which mercury enters this zone through diffusion at the air-sea interface.

The oxic-anoxic interface or chemocline is characterized by processes involving the oxidation of reduced substances produced in the anoxic zone. These processes are described in the papers by Anderson and Baross et al. Anderson's paper suggests that this zone actually consists of a complex series of interfaces that can be modelled in terms of diffusional and thermodynamic properties. These interfaces are the habitat for chemosynthetic bacteria which participate in the oxidation of reduced H_2S and ammonia, and use the energy released for the incorporation of CO_2 into organic material (chemosynthesis).

Large quantities of dissolved and particulate substances pass through the anoxic bottom water but relatively little processing occurs in this zone. From the sediments, reducing gases diffuse upward through this layer to be oxidized at the chemocline (oxic-anoxic interface). A continuous rain of particulate material enters the anoxic zone from above. Some microbial processing of these particles will occur as they pass through the anoxic water, but much more will occur when the particles settle on the bottom. The absence of zooplankton in this zone further restricts the processing of particulates.

The sediments of Saanich basin are effectively permanently anoxic, creating an ideal laboratory for sediment geochemical studies. Devol describes a discovery of anaerobic methane oxidation in Saanich Inlet sediments. The existence of this process had been previously proposed but was difficult to demonstrate without the constant reducing conditions that occur in Saanich Inlet.

I.2 DEEP WATER RENEWAL IN SAANICH INLET, B.C.

D.J. Stucchi and L.F. Giovando

INTRODUCTION

Saanich Inlet is a 24 km long fjord located at the southeastern end of Vancouver Island (Fig. 1). The inlet is oriented in a north-south direction and has a single basin of maximum depth 228 m. A sill, which begins at the northern end of Saanich Inlet with a depth of 75 m extends eastward through Satellite Channel to Swanson Channel where it attains a depth of 65 m ("outer sill", Figure 2). Unlike the "classical" positive fjord, Saanich Inlet does not possess a significant source of freshwater at its head or, for that matter, anywhere along its length. The nearest major input of freshwater is the Cowichan River, some 10 km northwest of the seaward end of the inlet.

HYDROGRAPHY OF THE DEEP WATER

This short note will deal primarily with the deep waters of Saanich Inlet, i.e. those below sill depth (75 m). Oceanographic data were collected at depth in the inlet as long ago as 1927. A number of investigators - Herlinveaux (1962), Anderson and Devol (1973) and Pickard (1975) - have reported on various aspects of the oceanography of the inlet. The data set obtained by the Institute of Oceanography (UBC) from 1966 through 1973, and reported on by Pickard (1975), provides a good starting point for the description of the hydrography of the deep waters.

Pickard (1975) presents data from depths of 100 m and 200 m. At 100 m, a distinct annual cycle is apparent in temperature, salinity and dissolved oxygen content. Salinity and temperature peak in the 4th quarter, while oxygen reaches a minimum in the 4th quarter. At 200 m an annual cycle is not apparent. It is evident from these time series that renewal at 200 m depth is sporadic. In three (1969, 1971, 1972) of the six years for which there is a complete annual span of data, renewal can be inferred at 200 m by the changes in oxygen and salinity. In the other years, changes at 200 m were small, and it is not clear whether deep water renewal occurred.

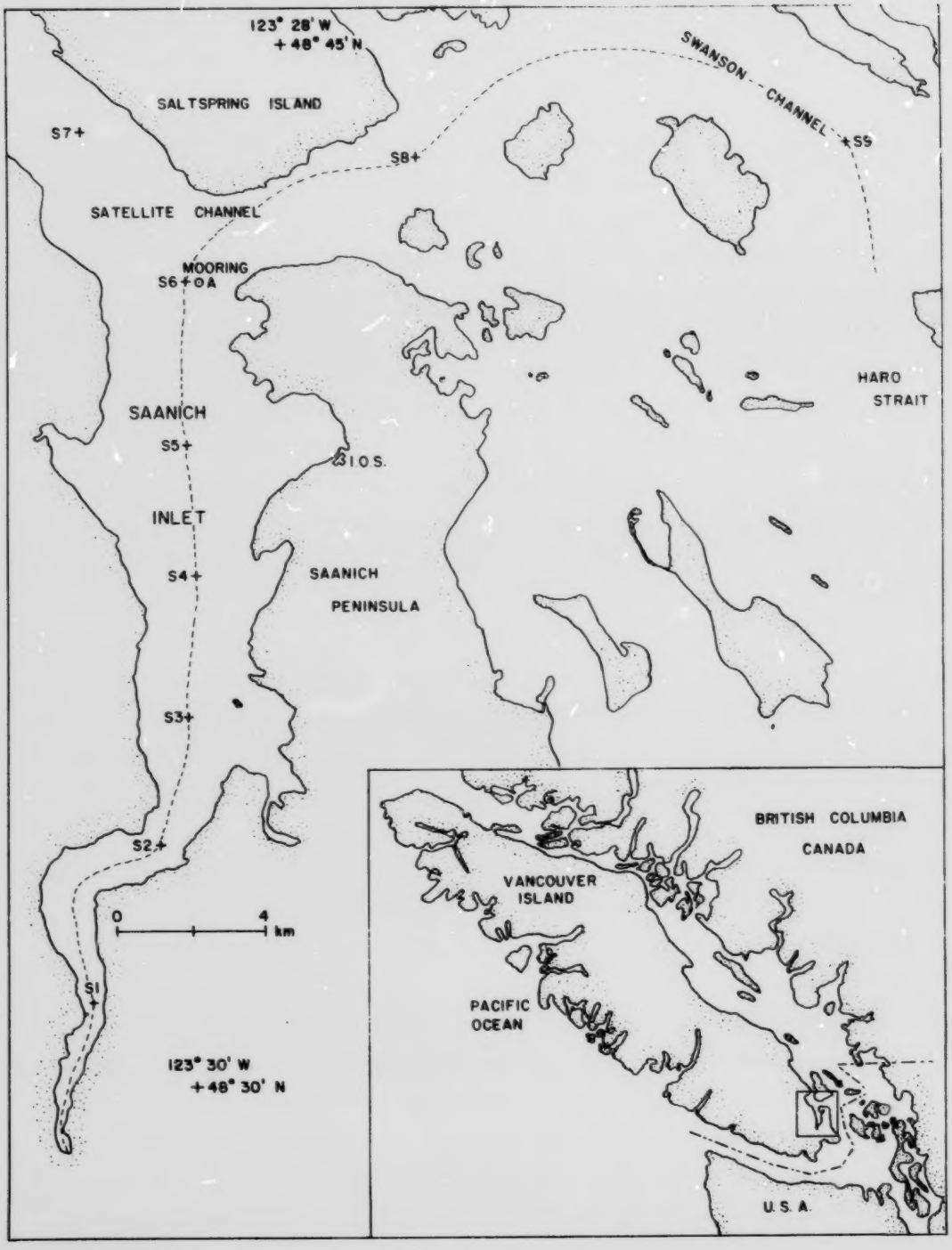

Fig. 1 Site map of Saanich Inlet and approaches. The locations of CTD stations S1 to S9 and mooring A are also shown.

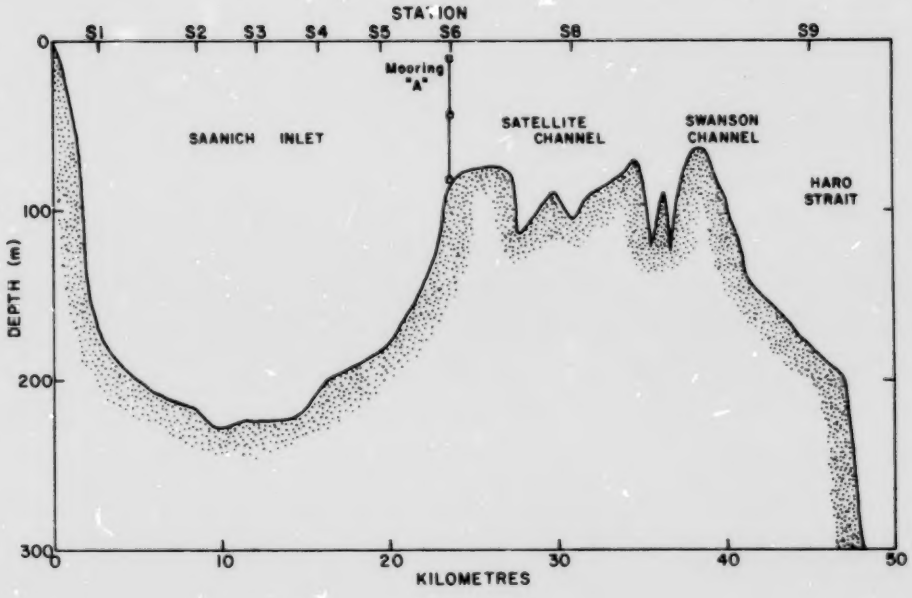

Fig. 2 Longitudinal depth profile from the head of Saanich Inlet, through Satellite and Swanson Channels to Haro Strait. The locations of CTD stations S1 to S9 and mooring A are also shown.

The Coastal Zone Oceanography group (CZO) at the Institute of Ocean Sciences (IOS) conducted 33 cruises in Saanich Inlet and its approaches (see Figure 1 for station locations) from April 1976 to December 1978, during which period temperature, salinity and dissolved oxygen content were measured at approximately monthly intervals (CZ 1980). The available density (σ_T) and dissolved oxygen data are plotted, for various depths at station S5 (Fig. 3). Values obtained at this station are considered to be representative of the deep waters of the entire inlet. An annual cycle is apparent at 100 m, and its behaviour is similar to that described above. At 125 m, dissolved oxygen peaked in the 3rd quarter; at 150 m and deeper, it was generally absent or low, except for a significant amount observed in August 1977. On the basis of these data it appears that there was renewal to the bottom in 1977 only.

Table 1

Salinity (‰)	100 m	200 m
UBC data 1966-73+	30.85 ± 0.06	31.28 ± 0.04
CZO data 1976-78	30.86 ± 0.16	31.21 ± 0.03
Temperature (°C)		
UBC data 1966-73+	8.55 ± 0.30	9.02 ± 0.07
CZO data 1976-78	8.82 ± 0.38	8.91 ± 0.05
Dissolved Oxygen Content (ml/l)		
UBC data 1966-73+	1.65 ± 0.35	0.19 ± 0.10
CZO data 1977-78	1.37 ± 1.27	0.02 ± 0.12*

*Only one measurement out of 26 was greater than zero (0.6 ml/l)
+UBC statistics from Pickard (1975)

It should be noted that to rely upon density alone to infer renewal at 200 m is inadequate, since the signal-to-noise ratio for density is very small at such depths. Ideally an independent measurement of dissolved oxygen or of some other chemical quantity (e.g. H_2S) would eliminate any doubt. An appreciation of the size of the variations at 100 m and 200 m can be gained by an examination of Table 1. This table compares means and standard deviations of salinity, temperature and dissolved oxygen for the deep waters of Saanich Inlet. The two data sets - UBC and CZO - are of comparable size.

The standard deviations at 200 m are very small; indeed, when these statistics are compared with corresponding ones from other inlets, Saanich Inlet deviations at 200 m are found to be the smallest, for any depth, by at least a factor of two. Pickard (1975) has remarked upon the small changes in the deep water properties of Saanich Inlet. The lack of exchange, and often anoxic conditions, in the deep water suggest a generally long residence time for this water; this in turn implies that there is, on average, a relatively small amount of energy available to drive the vertical turbulent diffusion in the deep waters. The reasons for the relatively small flux of energy to the deep waters is probably due to: 1) the absence of strong tidal currents,

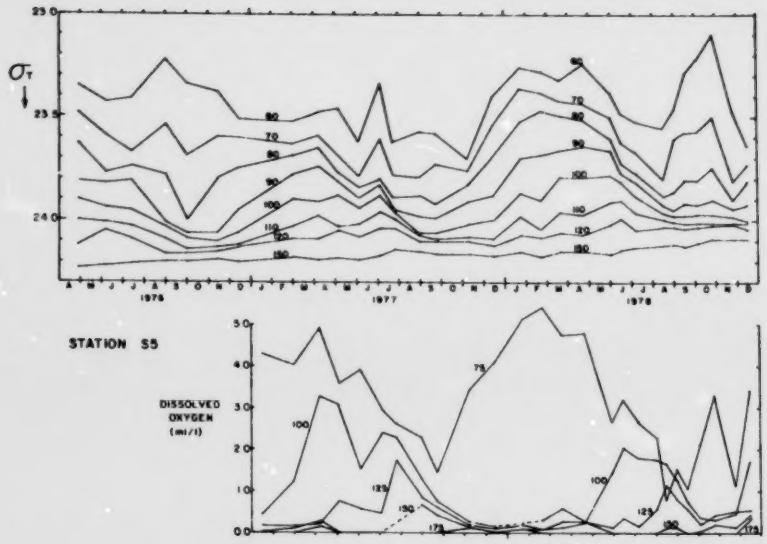

Fig. 3 Time series plots of σT and of dissolved oxygen content from S5, for various depths from April 1976 to December 1978 for σT and January 1977 to December 1978 for dissolved oxygen.

(only 10-15 cm.s^{-1} at the sill) 2) the lack of a vigorous wind field, such as that associated with strong diurnal winds, or with intense outflow winds that occur in some of the B.C. mainland fjords, and 3) the absence of a prominent estuarine circulation.

In an attempt to study the characteristics of the deep water renewal more intensively, the CZO group deployed moorings at the sill of Saanich Inlet from late August to late November 1978. The data from one of these moorings, A, at the northern end of the basin (Fig. 1) will be presented and discussed in connection with deep water renewal. Three Aanderaa current metres (RCM4) were utilized - at 14, 44 and 84 m - and an Aanderaa thermistor chain was positioned between 44 and 84 m. Only the data from 84 m depth will be shown, since no evidence of renewal events was apparent from data obtained with the other current meters.

The low-pass filtered salinity and current data from 84 m are plotted in Figure 4.

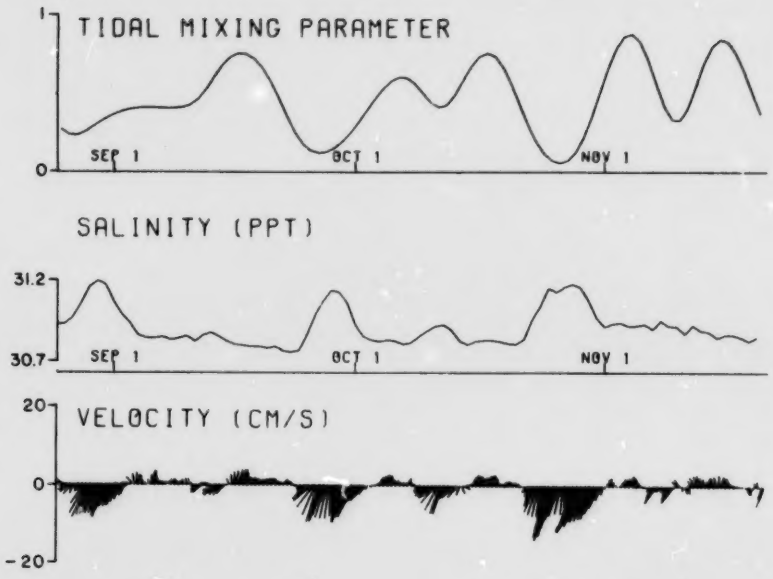

Fig. 4 Time series plots of filtered (low-pass) velocity and salinity data from mooring A at 84 m depth. Also included is a plot of the tidal mixing parameter in Haro Sound.

It is apparent from the results that there were three prominent inflow events - at the end of each of August, September and October. The duration of each inflow event was about 8-10 days, with inflow speeds of order 10 $cm.s^{-1}$, which could be slowed, or even arrested, by the ebbing tide. The temperature and salinity also exhibit strong oscillations associated with the tide; these are such that temperature and salinity are 180° out of phase. Peak salinities (minimum temperatures) occur after the peak inflows. Based on the fall-off of the vertical coherence in the temperature data from the thermistor chain (not shown here), the inflows extend from the bottom to about 72 m, a depth interval of about 10 to 14 m.

RENEWAL MECHANISM

The source for renewal water is considered to be Haro Strait, which is 25 km away from Saanich Inlet. In Satellite Channel the presence of Haro Strait water is readily confirmed by the similar "T-S" relationship.

During the August and October 1978 inflow events, renewal water was observed to be present above the "outer sill" level (65 m) in Haro Strait and in Satellite Channel. The longitudinal density gradient in both cases indicated a flow from Haro Strait westwards towards Saanich Inlet.

An annual cycle is discernible in Haro Strait from the 1968 data of Crean and Ages (1971). Their station #58 in Haro Strait is near CZO station S9 (Fig. 1). Data from station #58 indicate that in the summer, the surface waters (0-40 m) have annual minimum salinities, while the deepest waters (200--300 m) attain annual maximum salinities. The minimum surface salinities result from the annual maximum in the Fraser River outflow, while the maximum deep water salinities result from the movement of upwelled water from the west coast into Juan de Fuca Strait and eventually into Haro Strait. The annual cycle in salinity is therefore 180° out of phase between surface and bottom, with the "cross-over" depth being somewhere between 50 and 150 m. Water dense enough to renew the deep waters of Saanich Inlet is generally deeper than 100 m in Haro Strait, and must be raised over the 65 m "outer" sill to spread into Satellite Channel before renewal can occur.

The Crean and Ages (1971) data indicate considerable variability in the data which was not resolvable by 4 to 6 week sampling intervals which they used. Current meter, salinity and temperature data collected subsequently by IOS in July and August 1976 across the southern end of Haro Strait clearly show that this variability is basically fortnightly in nature (Webster 1977). This fortnightly signal is such that low surface salinities, high deep water salinities, and large vertical gradients occur between neap and spring tides, while higher surface salinities, lower deep water salinities and reduced vertical gradients occur after spring tides. The variations in the surface water and those at depth are out of phase - the "cross-over" depth being somewhere between 40 and 100 m.

The fortnightly signal results from the different tidal mixing regimes in Haro Strait - intense mixing occurring during spring tides and much reduced mixing during neap tides. The 1978 data from Saanich mooring A at 84 m shows a fortnightly pattern in salinity. Plotted in Figure 5, for comparison, is a parameter which is proportional to the daily mean of the squared tidal velocities in Haro Strait, and is representative of the variation in tidal mixing

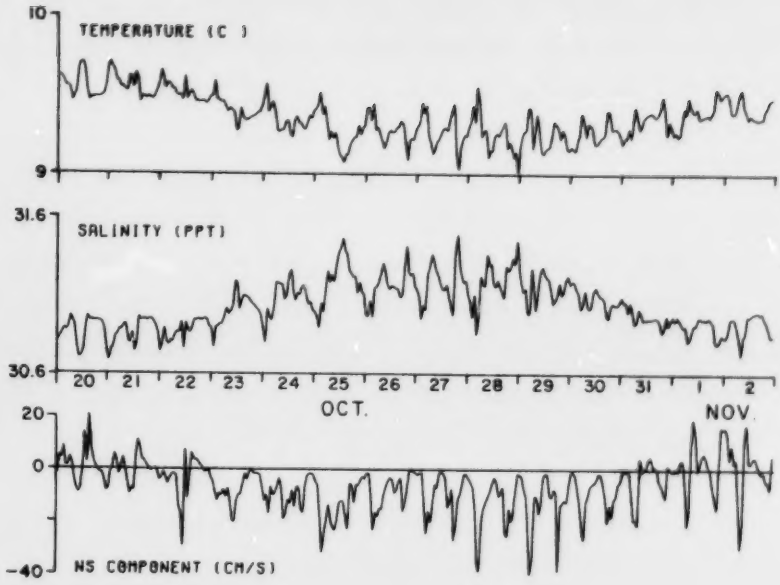

Fig. 5 Time series plots of temperature, salinity and N-S components of current at 84 m, during the inflow event at the end of October 1978.

there. The fortnightly change in this parameter is evident in Figure 5 - lowest values of the tidal mixing parameter occur during neap tides and highest values occur during spring tides. The relationship between salinity at 84 m and this parameter is such that during low values (at neap tides) higher salinity water is present at the Saanich Inlet sill. This relationship is similar to that observed in the deeper waters of Haro Strait.

In summary, the renewal mechanism in Saanich Inlet appears to be dependent on the annual variation in the salinities of Haro Strait. This variation is in turn modified by a superimposed fortnightly variation caused by tidal mixing throughout Haro Strait. It appears, from the 1978 data at least, that this fortnightly variation is responsible for presenting higher salinity (renewal) water above the outer sill depth and finally at the mouth of Saanich Inlet. The inflow to the inlet is further controlled, at even higher frequency, by the barotropic tide in that the flood tide accelerates the inflow and the ebb tide restricts, or even arrests, it. It may be noted that the interannual variations (trends) of the Saanich Inlet deep water and its renewals

may depend to a great extent upon inter-annual variability in the source waters themselves. However, the relationship can be verified, and explained, only by a long-term series of measurements; such a series is presently unavailable.

REFERENCES

Anderson, J.J., and A.H. Devol, 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuar. Coast. Mar. Sci. 1:1-10.

Herlinveaux, R.H., 1962. Oceanography of Saanich Inlet in Vancouver Island, British Columbia. J. Fish. Res. Board Can. 19:1-37.

Crean, P.B. and A.B. Ages, 1971. Oceanographic records from twelve cruises in the Strait of Georgia and Juan de Fuca Strait 1968. Victoria, Marine Sciences Branch, 1971. 5 vols.

Pickard, G.L., 1975. Annual and longer term variations of the deepwater properties in the coastal waters of southern British Columbia. J. Fish. Res. Board Can. 32(9):1561-1587.

Webster, I.W., 1977. A physical oceanographic study of Haro Strait: a data summary and preliminary analysis. Contract. Rep. 77-3. Institute of Ocean Sciences, Sidney, British Columbia.

Coastal Zone Oceanography Section, 1980. Salinity/temperature profiles in Saanich Inlet, B.C. Parts I and II., Pac. Mar. Rep. Ser. 80-5. Institute of Ocean Sciences, Sidney, British Columbia.

I.3 THE OXIC-ANOXIC INTERFACE IN SAANICH INLET

J.J. Anderson

INTRODUCTION

The oxic-anoxic interface in Saanich Inlet is typically considered to be a reaction layer between oxygen and hydrogen sulfide. A model developed by Broenkow (1969) suggests that the interface should be on the order of 1 or 2 metres thick. Observations suggest a layer of low oxygen and sulfide is tens of metres thick. Continuous profiles of a variety of chemical properties show the layer is actually a complex series of interfaces involving nitrogen, oxygen and sulfur compounds. In fact observations and a simple model suggest that the well-known sulfide-oxygen reaction might occur infrequently within the oxic-anoxic interface layer.

METHODS

The interface was measured with a profiling pump system described by Anderson and Okubo (1982). A profiling speed of 1 m/min was used giving undistorted profiles features on the order on 1 m thick. Phosphate, nitrate, nitrite, ammonia, and hydrogen sulfide were measured continuously from the pump effluent with an autoanalyzer, oxygen with a polarographic electrode, chlorophyll fluorescence with a fluorometer, and temperature and salinity with a CTD.

PROFILES

Four complete profiles of chemical properties were made through the interface near Elbow Point, 2/3 the way down Saanich Inlet, between July 9 and 10, 1977. In all profiles sulfide and nitrate had sharp slope changes and zero concentrations in a narrow layer at a depth of about 140 m. Oxygen had a sharp slope change at 120 m but the depth where oxygen reached zero varied between 120 and 140 m. The slope change in the ammonia profile was at a different depth each cast and was between 120 and 140 m. A nitrite peak and a pronounced step in the fluorescence profile occurred at about 130 m. The fea-

tures at 120, 130, and 140 m do not correspond with any significant changes in the temperature or salinity structures (Figs. 1 and 2).

INTERFACE CHEMISTRY

Figure 1 strongly suggests two interfaces: one at 120 m involving the reaction of oxygen and ammonia, and one at 143 m involving the reaction of hydrogen sulfide and nitrate. The nitrite peak at 130 m suggests a zone of denitrification between the two. Figure 2 has the lower interface, but the change in the ammonia slope is below 120 m suggesting it is involved with other reactions such as the reaction of ammonia and nitrate as postulated by Richards (1965). The oxygen-ammonia reaction is a well known chemotrophic bacteria energy source and the nitrate-sulfide reaction is thermodynamically favorable, and in the laboratory it can produce ammonia, nitrogen, and sulfate (Dilaman and Richards, unpublished manuscript). The increase in fluorescence is similar to that observed in the oxygen-nitrate interface at the top of the oxygen minimum zone of the eastern tropical North Pacific and suggests increased bacterial biomass (Anderson 1982).

The interfaces at 120 and 140 m suggest a series of reactions at different depth with some of the reaction products involving nitrogen diffusing between the reaction zones to create a recycling mechanism. This is shunted by the eventual production of molecular nitrogen in a low oxygen layer between the two interfaces (Fig. 3). In this model nitrate and ammonia nitrogen both end up as molecular nitrogen, while oxygen and sulfur combine as sulfate.

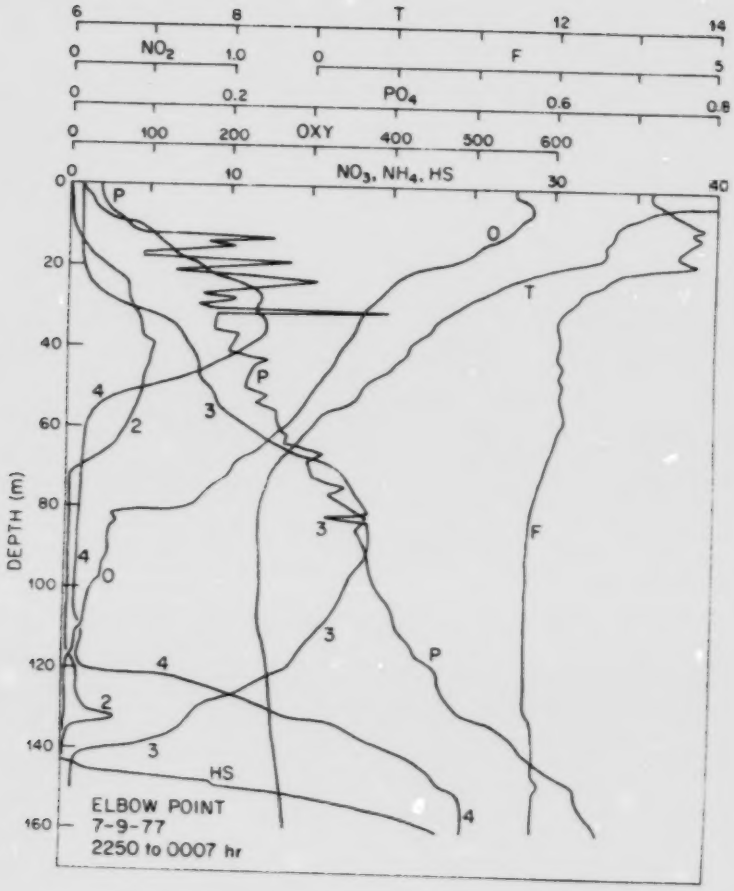

Fig. 1

Continuous vertical profiles in Saanich Inlet. Nitrite (2), Nitrate (3), Ammonia (4), Phosphate (P), Hydrogen Sulfide (HS), and Oxygen (OXY) in µg-at/ℓ , Temperature (T) in Centigrade, and Fluorescence (F) in relative units.

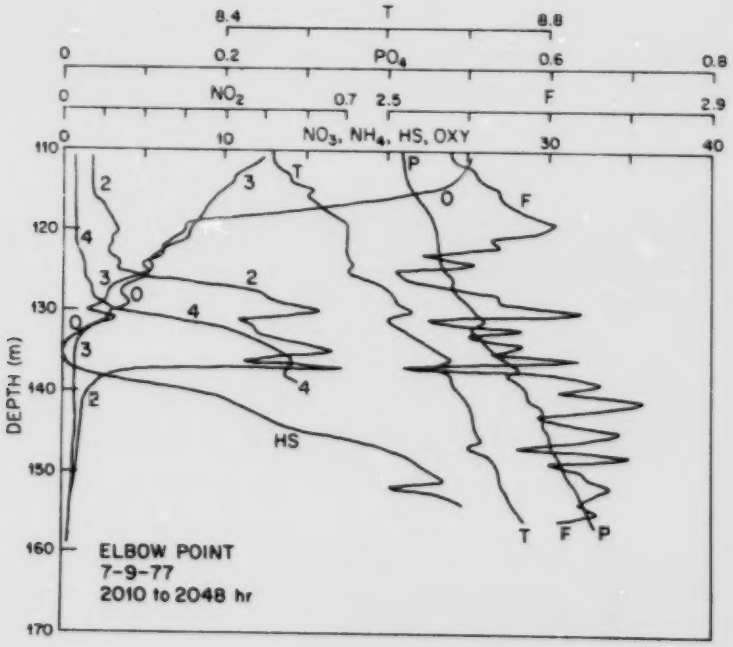

Fig. 2

Continuous vertical profiles in Saanich Inlet. Concentration units same as in Figure 1.

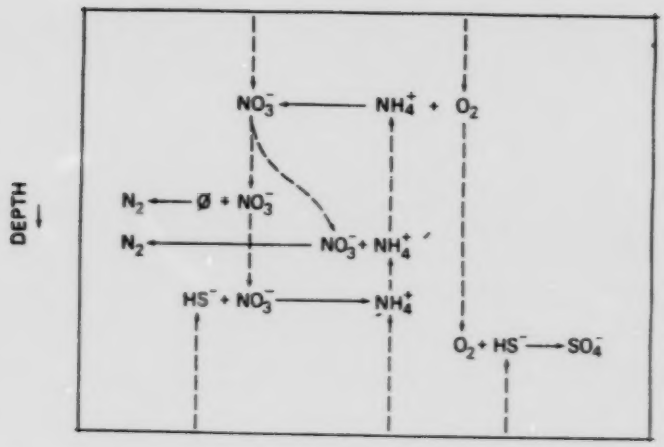

Fig. 3. Possible reaction and diffusion pathways for the chemical distributions in the oxic-anoxic interface. Solid horizontal lines depict reaction pathways, dashed vertical lines represent vertical diffusive transport pathways.

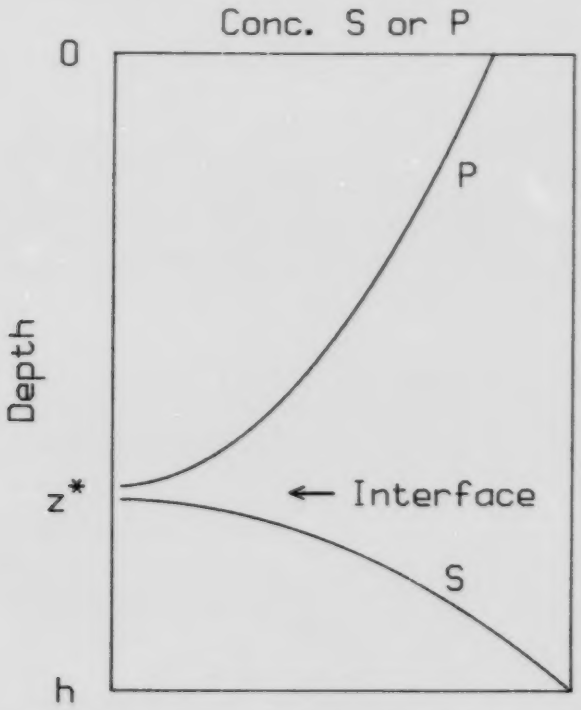

Fig. 4. Vertical profiles of P and S in water column of depth h, interface at depth z.

A MODEL FOR INTERFACE DEPTH

To illustrate how the interfaces can be separated in depth and why the sulfide-oxygen interface might be excluded, I present a simple model for the interface depth of two reactive properties, S and P. The interface depth at equilibrium is z* and h is the bottom. P is constant at z = 0 and has an *in situ* reaction rate Q above z*. S is diffused out of the sediments at a rate F and has an *in situ* reaction rate R below z*. At the interface, r molecules of S react completely with one molecule of P (Fig. 4).

Reaction-diffusion equations for the two layers are

$$K\,P'' + Q = 0 \qquad (0 < z < z^*)$$
$$K\,S'' + R = 0 \qquad (z^* < z < h)$$

where K is the vertical diffusion coefficient and (") designates a second derivative in the vertical direction z.

Boundary conditions are P(0) = Po and KS'(h) = F. The matching conditions at the interface are a concentration matching, P(z*)= S(z*)= 0 and an interface reaction flux equilibrium, rKS' (z*) = -KP'(z*).

Solutions in nondimensional form are

$$P(y) = A1 + B1\,y - C1\,y^2/2$$
$$s(y) = A2 + B2\,y - C2\,y^2/2$$

where the variables are y = z/h, p = P/Po, s = S/(Fh/K), the reaction diffusion ratios are $C1 = Qh^2/KPo$, C2 = Rh/F, the boundary conditions are p(0) = 1, s'(1) = 1, and the matching conditions at the interface x = z*/h are s(x) = p(x) = 0 and as'(x) = -p'(x) where a is a flux ratio defined a = rFh/KPo. The other constants are determined by the boundary and matching conditions and the interface depth is expressed

[1] $$(aC2 + C1/2)x^2 - a(1 + C2)x + 1 = 0$$

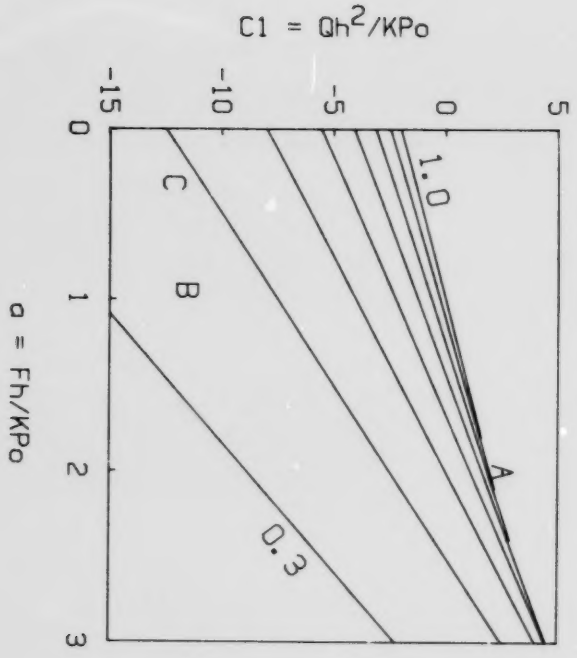

Fig. 5 Nondimensional interface depth x, in steps of 0.1, as a function of C1 and a, with C2 = 0, according to equation 1.

To investigate the interface depths using this model I take y = 0 to be the sill depth since oxygen and nitrate at this depth are replenished by horizontal advection over the sill. Then the O_2-NH_4 and NO_3-HS nondimensional interface depths are about x = 0.5 and 0.8 respectively. If a = 2 for the NO_3-HS interface, then C1 = 2 corresponding to the point A on the x = 0.8 isoline (Fig. 5). To determine the corresponding a and C1 for the O_2-HS interface and thus x note from the Redfield ratio $Q(NO_3) = -Q(O_2)/15$ and from the 80 m observations (Fig. 1) $NO_3(0) = O_2(0)$ 2/5. Then for the O_2-HS interface a = 0.9 and C1 = -12 if r is the same in oxygen-sulfide and nitrate-sulfide reactions. Since C2 remains unchanged, for C2 = 0 and the O_2-HS interface depth is x = 0.35 (point B in Fig. 5). Since the sulfide would be consumed at the nitrate-sulfide interface at x = 0.8, the oxygen-sulfide interface under these conditions would not exist.

To compare the model to the O_2-NH_4 interface C1 and a estimated for the O_2-HS interface are used. C1 is the same for both reactions and from Richards

(1965) the ammonia flux can be estimated as 1/3 the sulfide flux thus a = 0.3. The resulting equilibrium depth is x = 0.4 (point C, Fig. 5). For the simplicity of this model this result compares favorably with the observed interface depth x = 0.5.

CONCLUSIONS

From observations and a simple model, the following points are made:

1) The layer between oxic and anoxic waters is not dominated by a sulfide-oxygen reaction interface.

2) The layer contains two principal interfaces: a nitrate-sulfide interface at the bottom of the layer and an oxygen-ammonia interface at the top of the layer.

3) Ammonia can be involved in other reactions. This could explain the variability of ammonia in the layer.

4) A layer with denitrification can exist between the two interfaces. Small amounts of nitrite accumulate here.

REFERENCES

Anderson, J.J., 1982. The nitrite-oxygen interface at the top of the oxygen minimum in the eastern tropical North Pacific. Deep Sea Research 29: 1193- 1202.

Anderson, J.J. and A. Okubo, 1982. Resolution of chemical properties with a vertical profiling pump. Deep Sea Research 29:1013-1019.

Broenkow, W.W., 1969. The distribution of nonconservative solutes related to the decomposition of organic material in anoxic basins. PhD. Dissertation, Univ. Washington. 207 pp.

Richards, F.A., 1965. Anoxic basins and fjords. In: Riley, J.P. and G. Skirro, (eds.). Chemical Oceanography Vol. 1. Acad. Press, London, pp. 611-645.

I.4 CHEMISTRY AND MICROBIOLOGY OF DISSOLVED GASES IN SAANICH INLET

J A. Baross, M.D. Lilley and M. de Angelis

Measurements of the reduced trace gases CH_4, H_2, CO and N_2O were made throughout the water column during the summers of 1977, 1978 and 1981. From this data and concurrent microbiological observations, some hypotheses on the role of microbiological processes in the production and consumption of these gases are proposed. A summary of some of our observations and hypotheses is given below.

High supersaturations of H_2 (average saturation ratio of 22) were observed in 1977 and 1978. Results with an agar culture tube inoculated with this surface water indicted that there are microorganisms present in the Saanich Inlet surface water that are capable of producing H_2 under low O_2 conditions. Large bacterial cells and protozoa found in the surface waters may provide anaerobic microniches for H_2 production and other processes, such as denitrification, requiring low or zero O_2 levels. Evidence was found that nitrogen fixation was not the process responsible for the high levels of H_2.

Deeper in the water column H_2 was undersaturated but increased to slightly supersaturated levels in the anoxic zone. Hydrogen production by heterotrophic fermentative bacteria is postulated. However, since high levels of CH_4 and H_2S were also observed in the anoxic zone and H_2 is known to be consumed during methanogenesis and sulfate reduction, it is probable that both H_2 production and consumption are taking place in these waters and the production and consumption rates are nearly in balance.

In 1981, the water column was characterized by narrow layers of anomolous nitrogen species distributions and localized maxima of CO and H_2 which were found to correspond to peaks in denitrification potential. Similar relationships have been observed in Yaquina Bay, Oregon and in some Mt. St. Helens hydrothermal seeps. Although there is no known direct link between the production of these gases and denitrification, it is possible that the low oxygen levels may be controlling the various microbial processes taking place. It is suggested that incomplete oxidation of CH_4 and NH_4 in low

oxygen environments by chemosynthetic bacteria may result in the production of H_2 and CO.

Elevated surface levels of CH_4 with an average saturation ratio of 13 were also observed. A maximum occurred around 30 m in well-oxygenated water. Methane maxima in the upper water column of open ocean waters are common but the mechanism of production is not known since methanogenesis is believed to be a strictly anaerobic process. However, it is possible that, as for H_2 production, the endoplasm of protozoa, large bacterial cells or the intestinal tracts of higher organisms may provide anaerobic sites for CH_4 production.

The methane profiles were also characterized by minima at or near the oxic/anoxic interface. This is most probably due to the activities of CH_4 oxidizing bacteria. Methane increases to extremely high levels in the anoxic zone as the result of anaerobic bacterial decomposition of organic matter.

In general, we observed similar N_2O distributions as those observed by Cohen (Nature, 272, 235, 1978). N_2O is slightly supersaturated at the surface and undergoes a broad maximum in the upper oxygenated water column. From distributions of other nitrogen species, this maximum is attributed to the production of N_2O during nitrification. At the oxic/anoxic interface, N_2O generally disappears as it is used as a terminal electron acceptor in the decomposition of organic matter during denitrification. In some profiles where low oxygenated water occurred and anoxic conditions did not develop, localized N_2O maxima were observed which may be the result of either microbial nitrate reduction or nitrification.

REFERENCE

Lilley, M.D., J.A. Baross and L.I. Gordon, 1982. Dissolved hydrogen and methane in Saanich Inlet, British Columbia. Deep Sea Research 29:1471-1484.

I.5 FACTORS CONTROLLING THE PORE WATER DISTRIBUTION OF CARBON AND SULFUR SPECIES IN SAANICH INLET

A.H. Devol

The most important reactions controlling the observed distributions of solutes in the upper metres of the sediment column are those associated with the diagenetic oxidation of sedimentary organic material. For the most part, this oxidation is biologically mediated with the major reactions being oxygen reduction, combined inorganic nitrogen reduction, sulfate reduction and methanogenesis. Numerous models have been developed to describe organic matter oxidation and its concomitant effects on solute distribution (e.g. Berner 1980; Aller 1980a). However, testing of these models is usually difficult. The vast majority of marine sediments are in contact with an oxygenated water column and are inhabited by populations of benthic animals (Aller 1980b). As a result, solute and water exchange processes are complicated and the sediment column is not vertically stratified with respect to redox potential but frequently contains both oxidizing and reducing environments within the same depth strata. However, the highly reducing nature of Saanich Inlet sediments coupled with a frequently anoxic water column (Richards 1965; Anderson and Devol 1973) precludes the presence of benthic fauna. Thus, the inlet is an excellent location in which to study sedimentary carbon and sulfur diagenesis.

The highly reducing nature of Saanich Inlet is clearly evident from pore water profiles of sulfate, methane, alkalinity and total dissolved H_2S (Figs. 1 and 2). Sulfate is rapidly depleted in Saanich Inlet sediments and near zero values are always observed at 15 cm depth (Devol in press; Devol and Ahmed 1981; Murray et al. 1978). Within this zone, methane concentrations are low, but immediately below methane concentrations increase rapidly. Total dissolved H_2S is low at the surface, increases to a maximum at about 15 cm and decreases slightly below this depth. This type of dissolved H_2S profile is characteristic of highly reducing sediments and is due to H_2S production in the sulfate reduction zone and removal as FeS below (Goldhaber and Kaplin 1975).

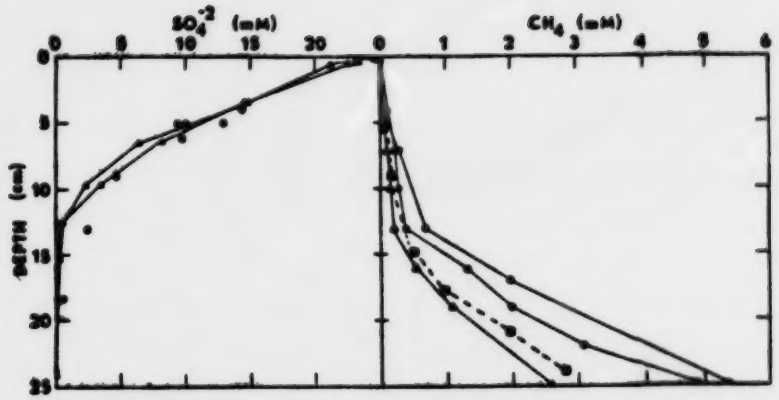

Fig. 1. Vertical distributions of sulfate and methane concentrations in Saanich Inlet.

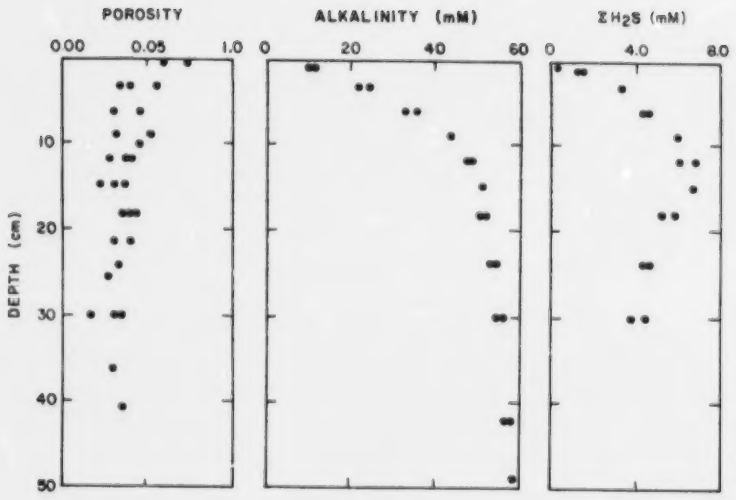

Fig. 2. Porosity, alkalinity and total dissolved sulfide in Saanich Inlet sediments.

The rapid depletion of pore water sulfate is due to the anaerobic bacterial oxidation of organic matter. Profiles of dissolved organic matter (DOC) and particulate organic matter (POC) are shown in Figure 3. As expected, POC decreases with increasing sediment depth as a result of in situ consumption. However, DOC increases with depth and indicates that production of DOC, rather than consumption is occurring in situ.

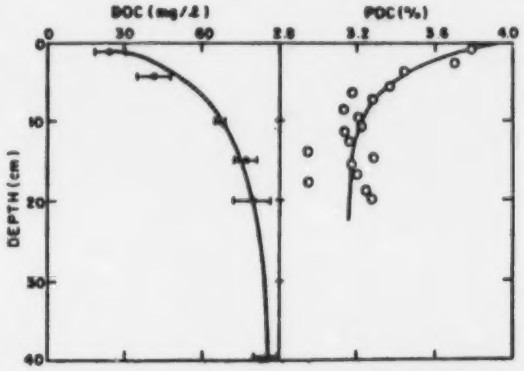

Fig. 3. Profiles of DOC and POC in Saanich Inlet sediments. POC is in % by dry weight. Solid lines show model fit using eq. 1. (from Devol and Ahmed 1981).

Selected vertical profiles of sulfate reduction rate, the dominant respiratory process in Saanich Inlet sediments are shown in Figure 4 and all rate data

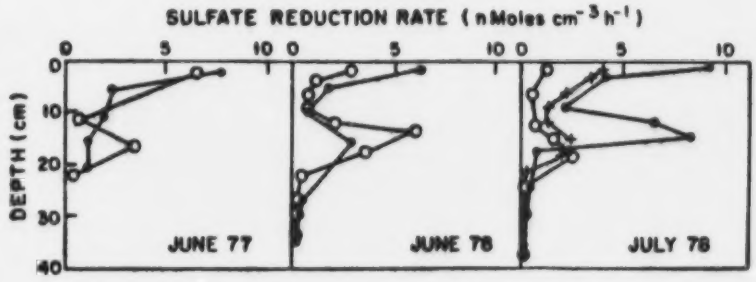

Fig. 4 Sulfate reduction in Saanich Inlet sediments (from Devol and Ahmed 1981).

presently available are given in Table 1. Although there is considerable variation between profiles, two features are always observed: First, sulfate reduction rates always decrease from some surface value; and second, there is invariably a subsurface local rate maximum at about 15 cm.

Table 1. Sulfate reduction rate data from Saanich Inlet. Data from June 1977 through July 1978 from Devol and Ahmed (1981). All values are nMoles $cm^{-3}.h^{-1}$. Average values were used for model fit.

Depth	June 1977	June 1978	June 1978	July 1978	July 1978	July 1978	May 1980	May 1980	June 1981	June 1981	Average	s.d.
0	8.3	5.8	3.2	4.2	1.3	9.4	10.0	5.6	3.4	12.0	6.32	3.46
3	-	-	1.3	3.5	-	-	3.7	1.1	1.5	1.2	2.05	1.21
6	-	1.5	1.2	1.9	0.5	4.2	-	1.4	1.3	0.8	1.60	1.13
9	-	-	0.8	1.6	-	1.9	1.0	-	2.9	0.8	1.50	0.82
12	1.0	0.8	2.3	1.0	0.8	6.7	-	4.1	1.5	0.6	2.09	2.04
15	3.8	-	6.3	2.5	1.3	8.0	2.1	5.1	0.7	5.6	3.93	2.47
18	-	2.9	3.6	1.6	2.4	0.8	0.3	0.9	0.2	1.5	1.58	1.17
21	0.25	-	0.3	-	-	-	0.2	0.3	0.04	0.3	0.23	0.10
24	-	0.6	-	0.3	0.01	0.1	0.06	0.08	0.02	0.08	0.16	0.19

In the absence of bioturbation the steady state distribution of any constituent can be described by the equation:

[1] $$\partial C/\partial z = 0 = \partial[\partial\phi D(\partial C/\partial z)]/\partial z - \partial(\omega\phi C)/\partial z - R,$$

where C is the concentration, ϕ is sediment porosity, D is the bulk sediment diffusion coefficient, z is depth, ω is the sedimentation rate and R is the net reaction or production rate (Berner 1980). It is generally assumed that sulfate reduction is first order with respect to oxidizable POC. Thus, because POC is nondiffusable, we can also write:

$$-\omega\frac{\partial G}{\partial z} = kG = \frac{R}{\alpha}$$

where G is the concentration of oxidizable POC, k is a first order rate constant, R is the sulfate reduction rate, and α is a stoichimetric coefficient equal to the number of sulfate ions reduced per atom of carbon oxidized. The solution to this equation with the boundary conditions, $G=G_0$ at $z = 0$ and $G \rightarrow G_\infty$ as $z \rightarrow \infty$, is $G=G_0 \exp[-(k/\omega)z]$. This solution requires that the concentration of oxidizable POC and therefore the sulfate reduction rate (αkG) decrease exponentially with depth. The best fit of this model to the Saanich

Inlet POC data is shown as the solid line in Figure 3. Within the scatter of the data the fit is reasonable.

With the appropriate boundary conditions equation 1 can also be used to model the distributions of DOC, CH_4 and SO_4. The DOC profile has been modeled by Devol and Ahmed (1981) assuming an exponentially decreasing DOC production rate. The model fit is again shown as the solid line (Fig. 3) and again the fit is excellent. However, when the model is applied to the sulfate data it breaks down (Fig. 5). Although the fit to the sulfate data is reasonable, the model predicted sulfate reduction rate does not display the consistently observed subsurface local maximum. This local maximum, then, indicates that some other oxidizable substrate is present at 15 cm.

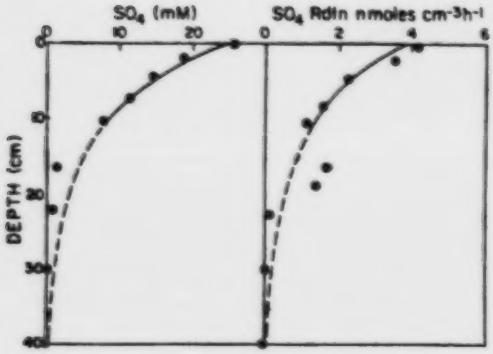

Fig. 5. Fit of the model [eq.1] to the sulfate profile in Saanich Inlet sediments. Also shown is the model predicted sulfate reduction rate profile.

The source of this other oxidizable substrate is probably upward diffusing methane (Devol and Ahmed 1981). Anaerobic methane consumption has frequently been proposed to explain other highly concave upwards methane profiles similar to those observed in Saanich Inlet (Reeburgh 1976; Barnes and Goldberg 1976; Martens and Berner 1977). That methane consumption is occurring in Saanich Inlet sediments can be easily seen in a simple mass balance calculation, assuming all methane consumption takes place between the surface and 25 cm depth in the sediments. The difference between the upward flux of methane at 25 cm and that at 0 cm should equal the areal rate of methane oxidation. Given a sediment diffusion coefficient of $10 \times 10^{-6} cm^{-2} \cdot sec^{-1}$ (molecular diffusion coefficient of $10^{1} \times 10^{-6} cm^{-2} \cdot sec^{-1}$; Sahores and Witherspoon 1970).

The respective fluxes are about 11 and 0.5 nmoles $cm^{-2} \cdot h^{-1}$. Thus, the net methane consumption rate would be about 10.5 nmoles $cm^{-2} \cdot h^{-1}$.

It has been assumed that the methane consumption reaction is first order with respect to methane concentration (Martens and Berner 1977). With this assumption it is possible to model the methane distribution using equation 1. With a first order rate term, $k[CH_4]$ and the boundary conditions $[CH_4]=0$ at $z=0$ and $[CH_4]=[CH_4]_x$ at $z=X$, the solution to equation 1 is:

$$[CH_4] = \frac{\exp[\alpha z] - \exp[\gamma z]}{\exp[\alpha x] - \exp[\gamma x]} \quad ,$$

where

$$\alpha = \omega + \frac{(\omega^2 + 4kD)^{-1/2}}{2D}$$

and

$$\gamma = \omega - \frac{(\omega^2 + 4kD)^{-1/2}}{2D}$$

The fit of the model to the observed profiles is shown in Figure 6. All profiles can be very well fit with a k value of $2.5 \times 10^{-7} sec^{-1}$. The dotted line indicates the methane profile expected with no consumption, i.e. k=0. Reeburgh (1976, 1981) and others (Devol and Ahmed 1981) have proposed that the anaerobic methane consumptions reaction is methane oxidation at the expense of

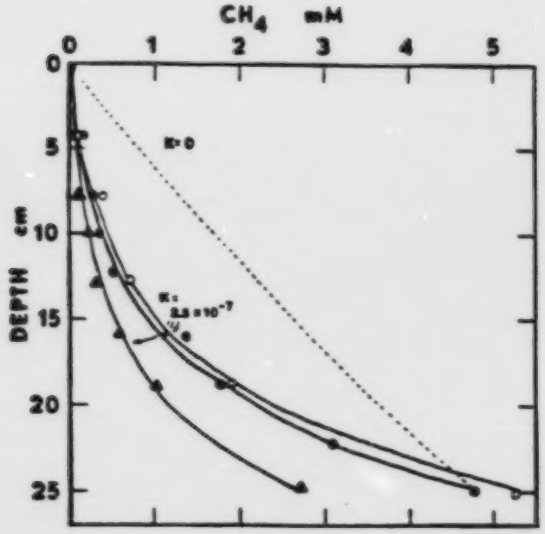

Fig. 6. Model fit [eq.1] to the observed methane profiles.

sulfate, viz:

$$CH_4 + SO_4^{=} \rightarrow HS^- + HCO_3^- + H_2O.$$

If methane is indeed oxidized by sulfate in Saanich Inlet sediments it is an important factor in the overall geochemical cycle of sulfur in the inlet. Comparison of the methane oxidation rate calculated previously, 10.5 nmoles $cm^{-2} \cdot h^{-1}$, with the integrated average sulfate reduction rate 27.1 nmoles $cm^{-2} \cdot h^{-1}$ (Table 1 averages) indicates that potentially about 39% of the downward sulfate flux is consumed by methane oxidation. This estimate is lower than the 75% estimated by Murray et al. (1978), but nevertheless points out the importance of the process.

In order to verify the occurrence of methane oxidation in Saanich Inlet sediments direct measurements of methane oxidation were made (Devol in press). The measurement technique was basically that of Reeburgh (1980) - that is, incubation with $^{14}CH_4$ and recovery of $^{14}CO_2$. The results of these incubation experiments are shown in Figure 7. Observed methane oxidation rates were low at the sediment water interface and increased with increasing depth to a maximum at 15 cm. Below this depth the rate of methane oxidation decreased and by 25 cm rates were almost zero. Also shown in Figure 7 is the average sulfate reduction rate profile. These data indicate that anaerobic methane oxidation definitely takes place in Saanich Inlet sediments and the co-occurence of peaks in both the methane oxidation and sulfate reduction rate profiles strongly suggests that sulfate serves as the oxidizing agent, either directly or indirectly via reactions coupled to other substrates.

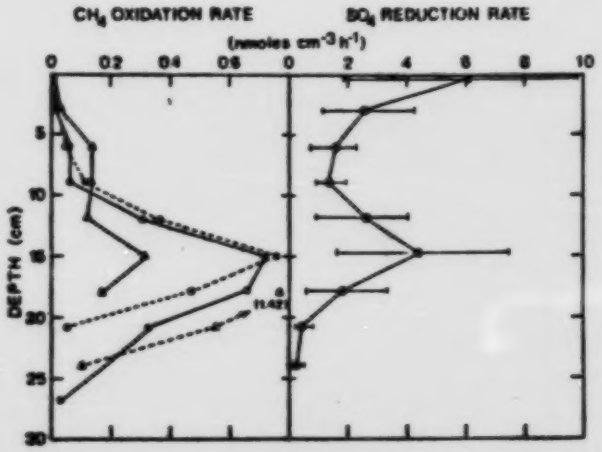

Fig. 7

Methane oxidation and sulfate reduction rate profiles in Saanich Inlet sediments. The sulfate reduction rates are averages and the bars show the range (from Devol, in press).

The peak in observed methane oxidation rate indicates that the methane model presented earlier is wrong. In formulating the model it was assumed that methane oxidation was first order with respect to methane concentration. Thus, because methane concentration increases continuously with depth, the model predicted methane oxidation rate would also increase continuously with depth. The model and the observed distributions are clearly different. It is interesting to note that the peaks in the methane oxidation rate and sulfate reduction rate occur at a depth where both methane and sulfate concentrations are very low. Thus, at this depth it is difficult to tell whether the concentration of methane or the concentration of sulfate is rate limiting. We are currently developing a two layer model for Saanich Inlet sediments (Devol, Anderson, Kuvila and Murray submitted). In the upper layer where sulfate concentrations are high, organic matter or methane is assumed to be rate limiting. In the lower layer where sulfate concentrations are low, sulfate is assumed to be rate limiting. This model reproduces both the subsurface local maximum in the sulfate reduction rate and the mid-depth maximum in the methane oxidation rate. The two rate peaks are located at the same depth - the depth of transition from organic matter rate limitation to sulfate rate limitation.

REFERENCES

Aller, R.C., 1980a. Quantifying solute distributions in the bioturbated zone of marine sediments by defining an average microenvironment. Geochim. Cosmochim. Acta, 44:1955-1966.

Aller, R.C., 1980b. Diagenesis near the sediment water interface of Long Island Sound. I. Decomposition and nutrient geochemistry (S, N, P.). Adv. Geophys. 22:235-348.

Anderson, J.J. and A.H. Devol, 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuar. Coast. Mar. Sci. 1:1-10.

Barnes, R.O. and Goldberg, E.D., 1976. Methane production and consumption in anoxic marine sediments. Geology. 4:297-300.

Berner, R.A., 1980. Early diagenensis: A theoretical approach. Princeton. Princeton University Press. 241 pp.

REFERENCES cont'd

Devol, A.H. and Ahmed, S.I., 1981. Are high rates of sulphate reduction associated with anaerobic oxidation of methane? Nature. 291:407-408.

Devol, A.H. (In press). Methane oxidation rates in the anaerobic sediments of Saanich Inlet. Limnol. Oceanogr.

Devol, A.H., J.J. Anderson, K. Kuivila, and J.W. Murray. (Submitted) A model of coupled sulfate reduction and methane oxidation in the sediments of Saanich Inlet. Geochim. Cosmochim. Acta.

Goldhaber, M.B. and I.R. Kaplan, 1975. Controls and consequences of sulfate reduction rates in recent marine sediments. Soil Science 119:42-55.

Martens, C.S. and R.A. Berner, 1977. Interstitial water chemistry of anoxic Long Island Sound sediments. I. Dissolved gases. Limnol. Oceanogr. 22:10-25.

Murray, J.W., V. Grundmanis and W.M. Smethie Jr., 1978. Interstitial water chemistry in the sediments of Saanich Inlet. Geochim. Cosmochim. Acta. 42:1011-1026.

Reeburgh, W.S., 1976. Methane consumption in Caracao Trench waters and sediments. Earth Planet. Sci. Lett. 28:337-344.

Reeburgh, W.S., 1982. A major sink and flux control for methane in marine sediments: Anaerobic consumption. In: Dynamic Environment of the Ocean Floor. (Eds. Fanning and Manheim). Lexington Books, pp. 203-217.

Richards, F.A., 1965. Anoxic basins and fjords. Pages 611-645 In: J.P. Riley and G. Skirrow (eds.). Chemical Oceanography, Vol. I. Academic Press, New York.

Sahores, J.J. and P.A. Witherspoon, 1970. Diffusion of light paraffin hydrocarbons in water from 2°C to 80°C. In: Adv. in Organic Geochem., 3rd Int. Cong. 1966 (G.D. Hobson and G.C. Speers, eds.). Pergammon Press, N.Y. pp. 219-230.

I.6 MERCURY TIME SERIES IN SAANICH INLET

X. Lu, W.K. Johnson and C.S. Wong

Time series for total, labile and dissolved mercury in sea water were determined at Station 5 of Saanich Inlet from February to November, 1982. At the same time, time series for salinity, temperature, oxygen and sulfide profiles were also determined.

The measurement of total mercury in the pore water of the sediment in Saanich Inlet and in trapped particulates was carried out during some of the cruises as were particulate organic carbon (POC), nutrients and chlorophyll a in the sea water column.

There are very different properties involved in the behaviour of mercury in the two Saanich Inlet regimes. The concentration of total mercury in the upper zone (above 100 m depth) was around 1 $ng \cdot l^{-1}$ Hg in most cases. This represents the lowest concentration of total mercury yet found in any sea water (Olafsson 1982; Matsunga et al. 1975; Mukherh and Kester 1975; Fitzgerald and Lyons 1975).

At the same time a higher flux of mercury, 0.01 - 0.02 $\mu g \cdot cm^{-2} \cdot y^{-1}$ from sea water to sediment was obtained, as compared with the 0.001 $\mu g \cdot cm^{-2} \cdot y^{-1}$ calculated by Mackenzie et al. (1979). This flux rate is close to that of air to sea; i.e., 0.01 $\mu g \cdot cm^{-2} \cdot y^{-1}$, Mackenzie et al. (1979). The high flux rate of mercury from sea water to sediment would account for the low concentration of mercury in the sea water column.

The vertical distribution of sulfide in bottom sea water can be approximated by eddy diffusion. An eddy diffusion coefficient of 0.46 $cm^{-2} \cdot sec^{-1}$ similar to that of radon in lake waters was used. The eddy diffusion of sulfide coupled with the similarities of the total dissolved and particulate mercury curves with that of sulfide, as well as the high concentrations of mercury in the pore water (about 2-60 $ng \cdot l^{-1}$ Hg) suggests that the sulfidic conditions can cause the particulate associated mercury to dissolve with subsequent diffusion of dissolved mercury upward from the bottom and also the resuspension of the particulate mercury. It can be concluded, therefore, that

the sulfidic condition is a main factor controlling the behaviour of mercury in the bottom zone.

The labile mercury in the sea water consists mainly of inorganic mercury which remains relatively constant at all depths and during all seasons. The labile and dissolved mercury were the main species of mercury occupying the upper zone, which implies that the diffusion of elemental mercury from air to sea could be the main process of mercury flux rather than the wash-out of rainfall.

The coefficient of diffusion in boundary micro-layers of sea water was estimated using the Lerman method (1979) as 1.6×10^{-4} $cm^{-2} \cdot sec^{-1}$. The diffusion of mercury from air to sea and the production of phytoplankton, indicated by POC and chlorophyll, can be used to explain the variation of mercury in the upper zone during certain seasons.

The high concentration of total mercury and low concentration of labile mercury (about 1.8 - 2.2 $ng \cdot l^{-1}$ Hg) in pore water proves that the organic mercury in the bottom zone results mainly from the dissolution of mercury from the particulates under the reducing conditions and the diffusion of organic dissolved mercury in pore waters upward from the bottom.

The plots of both total mercury vs. dissolved mercury and dissolved mercury vs. particulate mercury show a linear correlation for both data sets. The flux rate of mercury from sea water to the sediment changed with the seasons much less than the flux rate of POC did. These facts suggest that the dissolved and particulate mercury was in a state of ideal equilibrium.

REFERENCES

J. Olafsson, 1982. Mercury concentrations in the North Atlantic in relation to cadmium, aluminum and oceanographic parameters (in press).

K. Matsunaga, N. Nishimura and S. Konishi, 1975. Mercury in the Kuroshio and Oyashio regions and the Japan Sea. Nature 258, 224.

REFERENCES cont'd

P. Mukherh and D.R. Kester, 1979. Mercury distribution in the Gulf Stream. Science, 204, 64.

W.F. Fitzgerald and W.B. Lyons, 1975. Mercury concentration in open-ocean water: sampling procedure. Limnl. Oceanogr., 20, 468.

F.T. Mackenzie, R.J. Lantzy, and V. Patterson, 1979. Global trace metal cycles and predictions. Mathem. Geol. 11, 99.

A. Lerman, 1979. Geochemical processes. Water and Sediment Environments, John Wiley and Sons Inc. 481 pp.

I.7 SAANICH INLET AS A LABORATORY FOR TESTING NEW INSTRUMENTS AND APPROACHES TO OCEANOGAPHIC MEASUREMENT.

D.M. Farmer

The proximity to the Institute of Ocean Sciences of a deep, relatively quiet inlet provides the opportunity for testing many of the instruments now being developed, under nearly ideal conditions. Some recent developments in acoustic technology that may be of fairly general interest are described, including correlation measurements of biological scatterers and scintillation measurements for probing turbulent flows. Plans for future deployments are also described.

II. PLANKTONIC PROCESSING OF CARBON IN SAANICH INLET

II.1. OVERVIEW

F.A. Whitney

The restricted water movement within Saanich Inlet simplifies modelling of biological processes. The papers in this section show that it is possible to study, in detail, phytoplankton responses to nutrient supply and the effects of grazing on sedimentation.

Parsons found that a highly productive biological front exists where mixed waters of Satellite Channel meet stratified inlet waters. He found that the productivity of this front is influenced by tidal amplitude. In summer, high flood tides carry nutrient enriched waters further into the inlet, stimulating phytoplankton growth. An intrusion of nutrient-rich channel water was observed by Iseki and Wong during their spring bloom study.

Hobson suggests that further inside the inlet the supply of nutrients to phytoplankton is controlled by vertical mixing processes within the photic zone. He reports that strong vertical nitrogen gradients exist in the upper 15 m while horizontal gradients are minimal.

The transfer of organic carbon from surface waters to the sediment is both efficient and rapid. Migrating zooplankton graze year round, egesting fast-sinking fecal pellets. Iseki and Wong estimate that 12% of the primary production from a spring bloom was sedimented. In winter, Whitney and Wong found that sedimentation rates of organic carbon exceeded primary production. This suggests that some resuspension of particulates occurs in water, perhaps from the shallow bays of the inlet.

II.2 CARBON CYCLING IN THE SHALLOW WATERS OF SAANICH INLET

F.A. Whitney and C.S. Wong

PLANKTON STUDIES, 1975-78

Several papers, in which the plankton populations of the surface waters of Saanich Inlet were described, were produced during the period that the CEPEX grant was operating. During the winter, nano-flagellate biomass remains an order of magnitude higher than that of diatoms (Takahashi et al. 1978). Co-existing with these algae is the photosynthetic ciliate Mesodinium sp., the most abundant micro-zooplankton, the copepods Pseudocalanus minutus, Oithona helgolandica and Paracalanus parvus are dominant (Koeller et al. 1979).

It was calculated that ciliates could ingest a maximum of 30% of the primary production in winter, although this estimate is likely high (Takahashi and Hoskins 1978). Koeller et al. (1979) found that Pseudocalanus could obtain its energy requirements from grazing on the winter nano-flagellate population. Copepod ingestion rates sharply increased when nano-flagellates produced a mini-bloom two weeks before the spring diatom bloom (Table 1). It is apparent, however, that winter phytoplankton production significantly exceeds grazing by shallow water zooplankton.

Additional work by Takahashi et al. (1977) has provided enough data to plot yearly primary production in Saanich Inlet (Fig. 1). Winter rates averaged 20 mg $C \cdot m^{-2} \cdot d^{-1}$, while summer production averaged 1100 mg $C \cdot m^{-2} \cdot d^{-1}$. Summer phytoplankton growth is characterized by a series of diatom blooms that are triggered by periodically increased nutrient levels in the upper 20 m.

CARBON FLUX STUDIES, 1979-82

Since 1979, we have been involved in studies which assess the transport and recycling of organic carbon. In the winter of 1979-80, we conducted three cruises in the central basin of the inlet, and at the same

time, moored a sediment trap at 50 m near station 8 (Fig. 2). The vertical transport of organic carbon (Table 2) ranged from 75 to 150 mg $C \cdot m^{-2} \cdot d^{-1}$, a rate considerably higher than the rate of primary production previously measured a the same location. Winter sedimentation increased during periods of high winds and heavy rainfall, suggesting that resuspension of shallow water detritus, and terrestrial runoff are major sources of organic carbon. However, because C/N rations of both basin sediments and trapped material are consistently between 7 and 12, terrestrial vegetation cannot be an important source of particulate organic carbon (Gucluer and Gross 1964). The abundance of fecal material in sediment traps requires that zooplankton continuously graze in shallow waters throughout the winter. Therefore, sources of particulate material must be identified that can supply particles several times faster than the previously measured primary production rate.

This has led to our current work in Saanich Inlet. We are assessing the importance of autotrophic and heterotrophic production at a series of stations. It is our hope that these measurements, in combination with more complete sediment trap data, will help identify the sources of particulate organic carbon that make the basin sediments so rich in organics.

REFERENCES

Gucluer, S.M. and M.G. Gross, 1964. Recent marine sediments in Saanich Inlet a stagnant marine basin, Limnol. Oceanogr. 9:359-376.

Koeller, P.A., J.E. Barwell-Clarke, F. Whitney, and M. Takahashi, 1979. Winter conditions of marine plankton in Saanich Inlet, B.C. Canada. III. Mezo-zooplankton, J. Exp. Mar. Biol. Ecol. 37:161-174.

Takahashi, M., D.L. Seibert and W.H. Thomas, 1977. Occasional blooms of phytoplankton during summer in Saanich Inlet, B.C. Canada, Deep Sea Res. 24:775-780.

REFERENCES cont'd

Takahashi, M., J. Barwell-Clarke, F. Whitney and P. Koeller, 1978. Winter conditions of marine plankton populations in Saanich Inlet, B.C. Canada. Phytoplankton and its surrounding environment, J. Exp. Mar. Biol. Ecol. 31:283-301.

Takahashi, M. and K.D. Hoskins, 1978. Winter conditions of marine plankton populations in Saanich Inlet, B.C. Canada. II. Micro-zooplankton, J. Exp. Mar. Biol. Ecol. 32:27-37.

Table 1. Stock and activity of plankton groups in Saanich Inlet surface waters.

Date	Phytoplankton[2] Carbon mg C·m^{-2}	Ciliate[1] Carbon mg C·m^{-2}	Primary[2] Production mg C·m^{-2}·d^{-1}	Copepod[3] Ingestion mg C·m^{-2}·d^{-1}
16 Dec '75	78	30	20	8.0
30 Dec	86	7.6	26	1.7
13 Jan '76	31	8.8	39	2.1
20 Jan	69	4.1	12	5.9
17 Feb	82	7.7	126	1.0
9 Mar	665	11	250	10.3
23 Mar	475	6.8	465	44

Samples integrated from 1) 0-5 m, 2) 0-10 m, 3) 0-20 m.

Table 2. Sedimentation rates at 50 m near station 8 in Saanich Inlet in 1980.

Date	POC mg C·m^{-2}·d^{-1}	C/N atoms	Fecal Pellet Carbon[1]
7-14 Jan	150	11.5	37
18-25 Mar	110	9.5	38
25 Mar-1 Apr	100	7.3	58
16-23 Apr	220	7.8	67
9-23 May	170	8.0	38

1) only intact fecal pellets included in estimate.

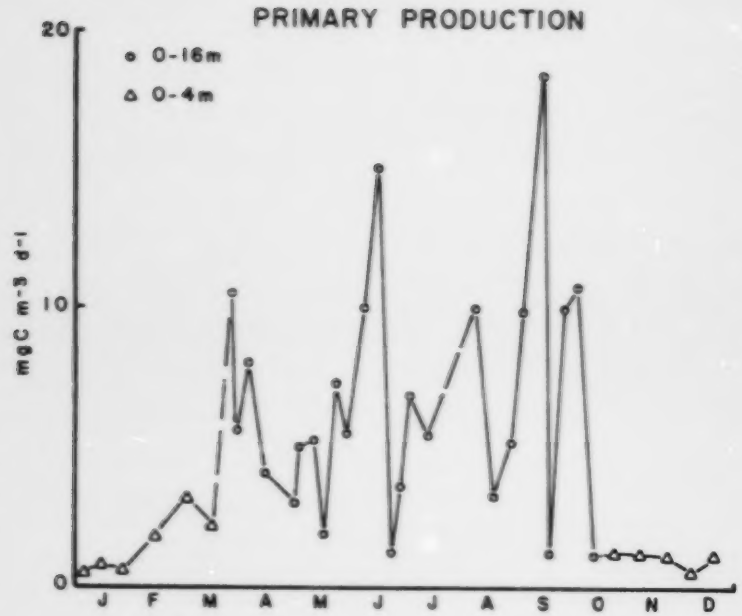

Fig. 1. Yearly cycle of primary production estimated by the ^{14}C method. Winter production was generally restricted to the upper 4 m of the water column, whereas, summer production extended to 16 m.

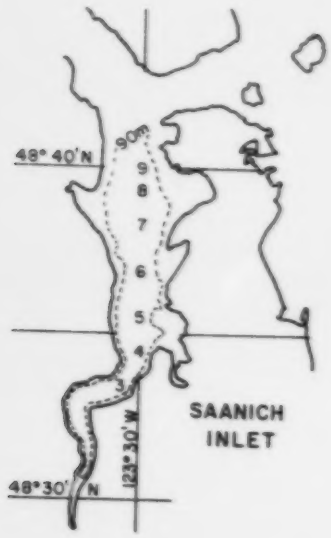

Fig. 2. Map of Saanich Inlet showing the stations sampled in 1979-80. Most measurements have been done in the vicinity of station 8.

II.3 ROLE OF ZOOPLANKTON FECAL PELLETS IN THE VERTICAL TRANSPORT OF ORGANIC MATTER IN SAANICH INLET

K. Iseki and C.S. Wong

Recent studies have indicated that rapidly sinking, relatively rare large particles such as zooplankton fecal pellets play an important role in the vertical transport and the distribution of various elements in the sea. The rapid transport mechanism probably permits the surface seasonal event, such as the spring phytoplankton bloom, to be observed in a short time throughout the water column.

Weekly observations on sedimentation, suspended particulate matter, primary productivity, zooplankton and nutrients were made between February 26 and April 24, 1979 at a CEPEX site in Saanich Inlet (Fig. 1). Sediment traps, consisting of two PVC cylinders, 48 cm high and 12.5 across the mouth (Iseki et al. 1981), were suspended at 10, 20, 30, and 50 m at 6-8 day intervals.

A pre-spring bloom of nano-flagellates (<15 μm) was observed on March 12, two weeks before the diatom spring bloom (Figs. 2 and 3). The diatom bloom dramatically developed from the surface to the deep water (down to 12 m) between March 26 and April 9. On April 17, particulate matter, Chlorophyll a, particulate organic carbon, and particle volume in the entire water column showed a sudden decrease which corresponded with a marked increase in salinity and nutrients. Several authors have observed that there was frequent mixing or exchange of surface and deep waters (Herlinveaux 1962; Anderson and Devol 1973; Takahashi et al. 1977), possibly due to a tidal current and an intrusion of a different water mass from outside. In spite of an increase of one order of magnitude in the POC concentration of the surface layer, no apparent increase in concentration was evident below 30 m during the sampling period.

On the other hand, sedimentation rates clearly increased throughout the entire water column just after the start of the diatom bloom. This was followed by the subsequent peak between April 10 and 18 at all depths and a sudden decline during the last collection period (Fig. 4). This similar sequence of material collected by traps throughout the water column is indic-

ative of rapid vertical transfer of material. Resuspension from the bottom sediment was also implied by infrequent high sedimentation at deeper depths, particularly at 50 m.

In addition, zooplankton numbers started to increase coincident with the pre-spring bloom. Direct observation and chemical analyses showed that the sedimented material below 20 m was predominantly zooplankton fecal pellets (Iseki et al. 1980). A significant fraction of the fecal pellets had a long cylindrical shape with the length of larger than 1 mm, easily recognized visually. Such large fecal pellets are egested by Euphausia pacifica, an abundant zooplankton species in Saanich Inlet, which migrates to the surface layer of night (Bary 1966).

Over the sampling period, the organic carbon input to the deep layer (30 m) of about 5.4 $gC.m^{-2}$ was equivalent to 12% of the primary production in the overlying water column, implying a high utilization of freshly produced organic matter within the water column.

This evidence suggests that the sedimented material in the deeper traps is not derived directly from fine suspended particles in the water but results from the effect of zooplankton grazing.

REFERENCES

Anderson, J.F. and A.H. Devol, 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuar. Coast. Mar. Sci. 1:1-10.

Bary, B. McK.,1966. Backscattering at 12 kc/s in relation to biomass and numbers of zooplanktonic aggregates in Saanich Inlet, British Columbia. Deep Sea Res. 1:656-666.

Herlinveaux, R.H., 1962. Oceanography of Saanich Inlet in Vancouver Island, British Columbia. J. Fish. Res. Bd. Can. 19:1-37.

REFERENCES cont'd

Iseki, K., F. Whitney and C.S. Wong, 1980. Biochemical changes of sedimented matter in sediment trap in shallow coastal waters. Bull. Planktol. Soc. Japan 27:27-36.

Iseki, K., M. Takahashi, E. Bauerfeind and C.S. Wong, 1981. Effects of polyclorinated biphenyls (PCBs) on a marine plankton population in controlled ecosystem enclosures. Mar. Ecol. Prog. Ser. 5:207-214.

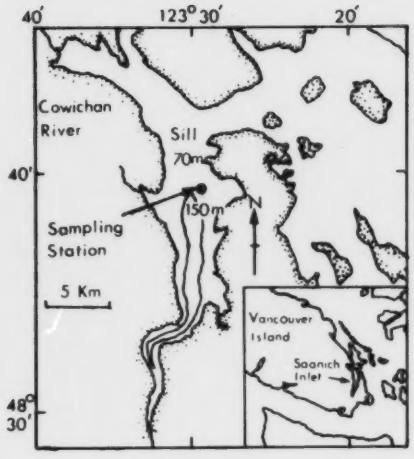

Fig. 1. Location of a sampling station in Saanich Inlet.

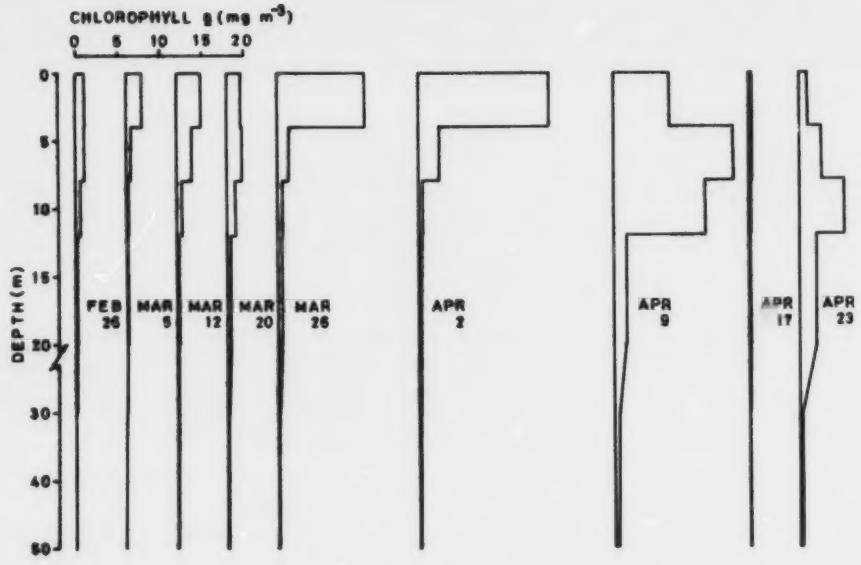

Fig. 2. Changes in chlorophyll a in the water column.

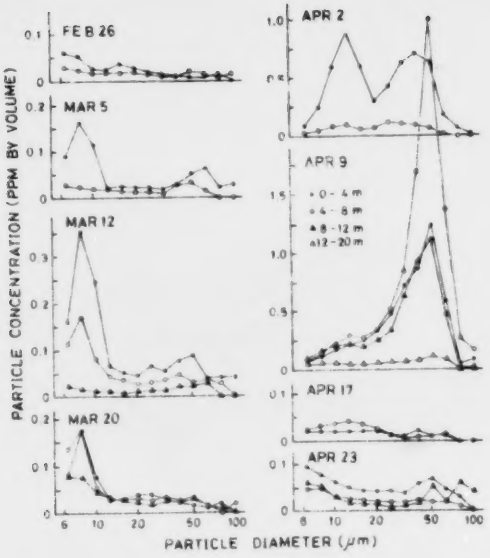

Fig. 3. Changes in particle size spectrum in the water column.

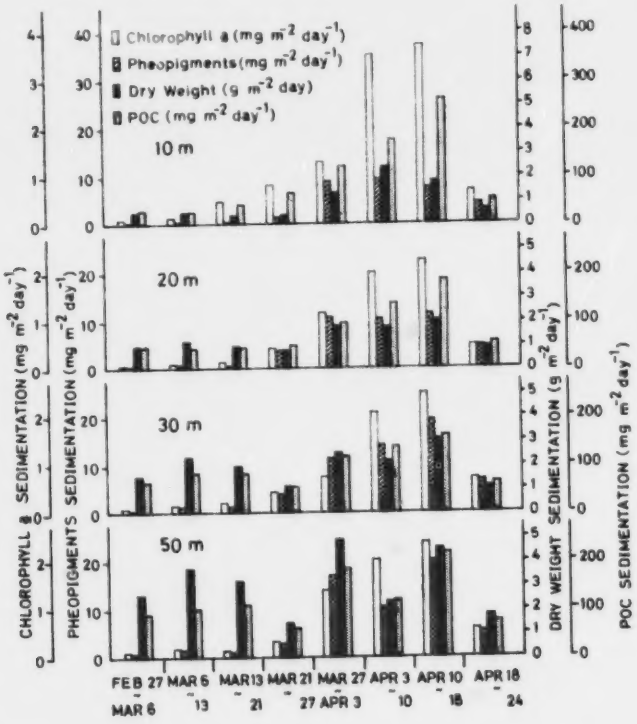

Fig. 4. Changes in primary production, chlorophyll a, and particulate organic carbon concentrations, zooplankton abundance and sedimentation rates.

II.4 NITROGEN AND THE BIOLOGY OF PHYTOPLANKTON IN SAANICH INLET

L.A. Hobson

Nutrient budgets for phytoplankton in Saanich Inlet have been studied at the University of Victoria since 1974. Ratios among the examined nutrients including nitrogen, phosphorus, and silicon support the contention that nitrogen is a potential regulator of phytoplankton production during summer months. For example, near-surface concentrations of NO_3-N vary between 14 and 24 $\mu m \cdot l^{-1}$ during winter months; they decline in March, reaching values less than 1 $\mu m \cdot l^{-1}$ of NH_4^+ by mid-May. Levels remain low until mid-July when they begin to increase, reaching winter concentrations by mid-September. This seasonal cycle has been observed for 7 years, but a definitive statement about regulation of production is difficult because concentrations are determined by phytoplankton demand, bacterial and animal regeneration, and temporal and spatial distributions of advection and turbulence. We have attempted to determine the magnitudes of these processes during the past 10 years.

Nitrogen demand by phytoplankton was estimated for the period, April through August, based on calculations using chlorophyll *a* concentrations, ratios of cellular carbon and nitrogen to chlorophyll *a*, and CO_2 uptake rates. Demands varied between 10 $ugN \cdot l^{-1} \cdot d^{-1}$ in May, July and August of 1978 and 1981, and 300 $\mu gN \cdot l^{-1} \cdot d^{-1}$ in April through June of 1975 and 1976. Bacterial metabolism was measured in 1981 from which maximum rates of regeneration were estimated, varying between 0.94 and 2.0 $\mu gN \cdot l^{-1} \cdot d^{-1}$ for July and May, respectively. Protozoan biomasses were measured from 1973 through 1976 and again in 1981 and were used with excretion rates taken from the literature to calculate values of nitrogen regeneration varying between 0.13 and 0.84 $ugN \cdot l^{-1} \cdot d^{-1}$ during May and August, respectively. Metazoan biomasses taken in 1978 were used to estimate rates of excretion, which varied between 0.76 and 1.2 $\mu gN \cdot l^{-1} \cdot d^{-1}$ during July and June, respectively. Percentages of nitrogen demand by plant cells provided by rates of regeneration and excretion varied between 0.5% in April of high primary production years and 34% in August of low primary production years. Thus, regeneration of nitrogen does not appear to balance nitrogen demand, except perhaps during

years of very low primary production. Therefore, physical processes must also be examined.

Horizontal advection and turbulence were estimated by measuring nitrogen gradients between Finlayson Arm and Satellite Channel in 1977. Values varied between 0.00 and 0.012 $\mu gN \cdot l^{-1} \cdot m^{-1}$ in July-August and June, respectively. Compared to these values, vertical gradients were much larger, varying between 3.1 and 55 $\mu g l^{-1} m^{-1}$ from 5 to 10 m in August and April, respectively. Apparently, vertical advection and turbulence could provide considerable amounts of nitrogen to the phytoplankton. However, quantification requires measurements of vertical velocities and coefficients of turbulent diffusion. Indirect calculation of these two processes have produced ambiguous results. Further attempts to measure them will be made during 1983 and 1984 using more sophisticated analytical methods than we have previously employed.

II.5 THE BIOLOGICAL FRONT AT THE MOUTH OF SAANICH INLET

T.R. Parsons

A biological front exists at the mouth of Saanich Inlet as can be illustrated from chlorophyll and primary productivity data (Figs. 1 and 2). The front is influenced by tidal motion and is generally strongest during periods of neap tides and weakest during the spring tide cycle. The ecology of the front is quantitatively different to waters exist in both environments. The 14 day cycle in front intensity may govern other biological events in the inlet.

The full text of this paper appeared in Parsons, T.R., R.I. Perry, E.D. Nutbrown, W.Hsuh and C.M. Lalli. 1983. Frontal zone analysis at the mouth of Saanich Inlet, British Columbia, Canada. Mar. Biol. 73:1-6.

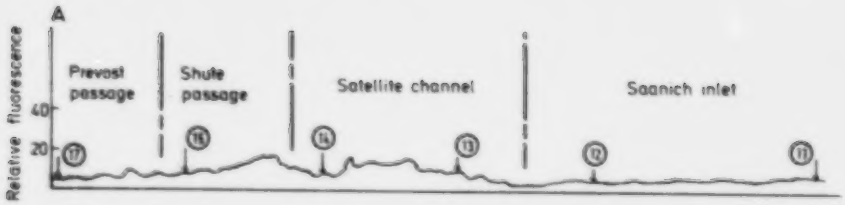

Fig. 1A Near surface chlorophyll fluorescence, June 1981, Saanich Inlet.

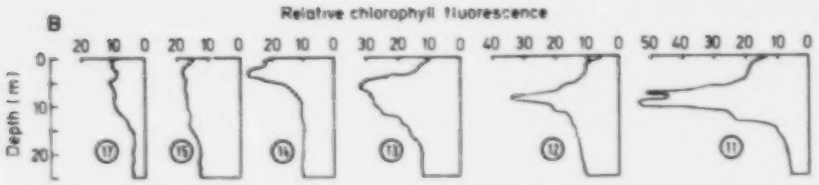

Fig. 1B Depth profiles of chlorophyll fluorescence.

Fig. 1C Temperature profile in the same region.

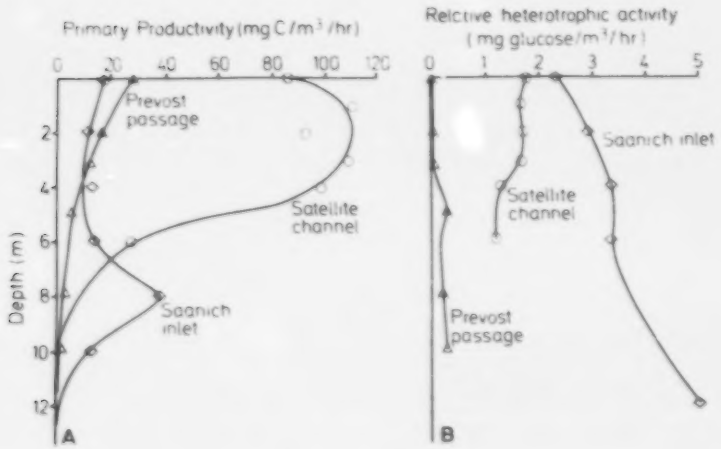

Fig. 2 Profiles of primary productivity and heterotrophic activity in the same region.

III. THE FAUNA OF SAANICH INLET

III.1. OVERVIEW

V.L. Tunnicliffe

Studies on fjord biology are surprisingly few in number. Unfortunately, much of the most extensive work - in Scandinavia - is not available to English readers. Fjords have a certain attractiveness to the biologist in that they frequently harbour deep water assemblages very close to land. Norwegian workers have found that fjords tend to act as refuges for deep water groups that are rarely found above bathyal depths. An essential feature of studies of such a habitat is their accessibility. It is possible to sample deep water from a small boat that would normally never venture beyond the continental shelf.

Many of the fjords of British Columbia are enclosed bodies of water whose physical and chemical characteristics are distinctive and predictable. Hydrographic characteristics may vary greatly; Observatory Inlet with high fresh water input; Bute with very high suspended sediment concentrations; Knight with considerable turbulence over its sill; Jervis with deep, clear, well-oxygenated waters; Howe Sound with temporal and spatial variability; and Saanich Inlet with low oxygen conditions. Each fjord provides the opportunity to study biotic features developing under a specific set of conditions.

Periodically or permanently anoxic basins are not rare and studies of biological activity within them are relevant to Saanich Inlet. Macro- and microplankton in many such basins (i.e. the Black Sea) show distinct productivity peaks above the anoxic layer (Karl 1982) similar to those in Saanich. Other similarities include the dense sulphur-bacterial mats found under the upwelling zone off Peru where oxygen levels are consistently low (Rosenberg et al. 1983). Open ocean basins such as the Cariacou Trench and the California Basin have very low macrofaunal populations due to low oxygen conditions (Rhoads and Morse 1971). Periodic anoxia in the Baltic Sea has destabilized the benthic populations and caused extensive mortality (Leppakowski 1969). The activities of man can cause depleted oxygen levels by inducing high

concentrations of organic matter; such events can result in mass mortalities (Levings 1980; Rosenburg 1976).

Numerous laboratory studies are also available to illustrate how metazoans react to decreasing oxygen concentrations. Many are summarized in Davis (1975) for fish and commercial species of invertebrates. A small abalone farm has been established on Finlayson Arm in Saanich and the possibility of opening a shrimp fishery in the inlet is under investigation. Considering the success of the sport-fishing industry in Saanich Inlet, the effects of low dissolved oxygen levels on commercial marine species is of more than just curiosity value.

Biological studies in Saanich Inlet have been aided greatly by the presence of the manned submersible Pisces IV stationed at Patricia Bay. She has now made over 500 dives in the inlet. Such a tool provides a rare opportunity to extend shallow water SCUBA work and remote studies with nets and bottles. The sub is of particular value to study plankton and nekton that are concentrated in patches and narrow bands. Methods and apparatus that make efficient and accurate use of the submersible are surprisingly difficult to design. Mackie and Mills (1983) present the results of comparative studies on plankton populations using Pisces and nets; with well-trained observers it is possible to obtain repeatable numerical observations from the sub. Such submersible observations have confirmed the identity of targets located by other means (Mackie, Section III.4). These dense layers of amphipods, euphausiids, Munida larvae and herring that concentrate just above the anoxic/oxic interface are particularly striking when seen from the submersible. Both these animals and the jellies studied by Mills (Section III.3) show daily and seasonal migration patterns related, in part, to light and oxygen conditions.

Extensive soft bottom communities of Saanich Inlet are limited to the shallows and to the deeper areas near the sill. Ellis (1971) found a stable community in the bottom sediments of adjacent Satellite Channel that was dominated by brittle stars and bamboo worms. A study of the new subtidal sediments in upper Saanich Inlet revealed only rare polychaetes (Beak 1976). Further down-inlet communities such as those of the sea-whip beds (Bamberton and Patricia Bay) and polychaetes and bivalves (the sill) become a little richer. Seasonal colonization of sediments has been described for intermit-

tently anoxic fjords elsewhere (Jorgensen 1980) but the extent of oxygen depletion is not as severe as Saanich. Although organic matter levels are high in the sediments the high sulphide levels make this an inhospitable habitat. However, one does wonder if an organism such as Solemya reidi - a gutless bivalve found in Alberni Inlet that harbours chemosynthetic symbiotic bacteria - might not make a happy home here.

The hard bottom community has no sediment buffer to ameliorate the overlying water conditions. Studies in other fjords of the world are limited to SCUBA-diving depths but provide some interesting comparisons to Saanich. The work of Gulliksen (1980) in Norway described the seasonal changes that occur in communities where surface water and photic characteristics govern a fairly stable and predictable assemblage. New Zealand fjord assemblages tend to have many taxa that are found in deeper Canadian water - animals such as brachiopods and corals (Richardson 1981). In addition to the scientific results, the methods of these researchers should be pertinent to those planning studies in Canadian fjords.

In Saanich Inlet the vertical walls - particularly of the upper inlet - provide substrata for an assemblage that appears to be structured in large part by the oxygen levels. Study of this habitat is limited to submersible observation and collection of sessile creatures and surface trapping of mobile crustaceans; many of the specimens examined by B. Burd in this volume were captured in this fashion. Valuable information can be assessed through the use of photography and trained observers. Austin's contribution addresses an important issue in the in situ study of epifaunal assemblages: identification and characterization of animals sighted. Although photographs are useful, corroborating observations must be made from the submersible; supplementary collections confirm the identifications. With the increased use of Pisces in Saanich Inlet better information on seasonal and yearly changes can be obtained. I have a study in progress to analyze community changes by repeated stereo photographs of reference markers that extend throughout the biotic zone of the cliff habitat.

The nature of hydrographic conditions in Saanich Inlet provide an opportunity to plan long-term work to investigate the physiological and

behavioural characteristics of animals that develop in response to fluctuating oxygen levels and to study the stability of a community experiencing such perturbations. Down to 50 m in Saanich Inlet, fleshy and coralline algae dominate. The density and diversity of the epilithic community then increases despite acute oxygen depletion below 80 m (Tunnicliffe 1981) and attached metazoans disappear abruptly below the anoxic boundary around 120 m. In this 30 m depth interval the character of the attached assemblage is radically different from that observed in other fjords in a similar depth range. Some major phyla such as the Enchinodermata and the Mollusca are virtually absent while other phyla are represented by restricted classes: demosponges are present but hexactinellids do not extend below 75 m; the sedentary polychaetes have limited representation. On the other hand certain groups appear to flourish in the low oxygen conditions: articulate brachiopods, one family of anthozoans and many families of ascidians dominate the sessile fauna.

Mobile animals - usually limited by higher oxygen demands - are few. This circumstance may help explain the very high abundance of sedentary animals who may no longer be predator-limited. One mobile creature with a fascinating behaviour is described by Burd (Section III.2). Munida quadrispina is able to tolerate very low oxygen conditions and is one of the first animals sighted when rising up from the anoxic zone. Its distribution appears strongly regulated by the oxygen levels and when the oxygen profile fluctuates, the squat lobsters begin to migrate. This animal may influence the Saanich Inlet food chain markedly because of its great abundance and its feeding habits: it has been seen to capture plankton from the water, graze on bacterial mats and prey on ascidians.

The ability of the cliff fauna to tolerate such low oxygen levels was initially a surprise. Previous estimates of oxygen tolerance by metazoans was estimated at a minimum level of 1.0 $ml.l^{-1}$ for calcareous animals and 0.3 $ml.l^{-1}$ for small soft-bodied animals (Rhoads and Norse 1971). Saanich Inlet provides the first look at a deep hard-bottomed community and one is lead to believe that adaptations to low oxygen levels may not be so difficult - after all, life did develop in a very low oxygen ocean. Life in deep water in Saanich is not problem-free: at times, the anoxic and H_2S-rich deeper water rises into the biotic zone. One sees a mass migration of the galatheid crabs,

closure of the brachiopods and ascidians, and contraction of the anemones. After one such event that lasted two weeks, the extent of survival was astonishing. However, massive graveyards of brachiopod and crab skeletons, and decaying black tissue spots on the rocks indicate that the oxygen fluctuations of Saanich can be deadly.

Saanich Inlet provides a welcome opportunity to study the long-term effects of oxygen depletion on biota of many different persuasions: plankton, nekton, infaunal and epifaunal benthos. Ships' crews might get tired of research excursions into Saanich Inlet but hopefully scientists will retain interest for a long time.

REFERENCES

Beak Consultants Ltd., 1976. Sampling and analysis of marine benthic fauna in Saanich Inlet. (Unpubl. Rep. Institute of Ocean Sciences, B.C.).

Davis, J.C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Board Can. 32: 2295-2332.

Ellis, D.V., 1970. A review of marine infaunal community studies in the Strait of Georgia and adjacent inlets. Syesis 4:3-9.

Gulliksen, B., 1980. The macrobenthic rocky-bottom fauna of Borgen-fjorden, North Trondelag, Norway. Sarsia 65:115-138.

Jorgensen, B.B., 1980. Seasonal oxygen depletion in the bottom waters of a Danish fjord and its effect on the benthic community. Oikos 34:68-76.

Karl, D.M., 1982. Microbial transformations of organic matter at oceanic interfaces: A review and prospectus. EOS 63 (5):138-140.

Leppakoski, E., 1969. Transitory return of the benthic fauna of the Bornholm Basin after extermination by oxygen insufficiency. Can. Biol. Mar. 10: 163-172.

REFERENCES cont'd

Levings, C.D., 1980. Benthic biology of a dissolved oxygen deficiency event in Howe Sound.B.C. In H.J. Freeland et al. (eds.). Fjord Oceanography (Plenum, New York). pp. 515-522.

Mackie, G.O. and Mills, C.E., 1983. Use of the Pisces IV submersible for zooplankton studies in coastal waters of British Columbia. Can. J. Fish. and Aqu. Sci. 40 (6):763-776.

Rhoads, D.C. and J.W. Morse, 1971. Evolutionary and ecologic significance of oxygen-deficient marine basins. Lethaia 4:413-428.

Richardson, J.R., 1981. Recent brachiopods from New Zealand - background to the study cruises of 1977-79. New Zeal. Jour. Zool. 8:133-143.

Rosenberg, R., 1976. Benthic faunal dynamics during successive following pollution abatement in a Swedish estuary. Oikos 27:414-427.

Rosenberg, R., et al., 1983, Benthos biomass and oxygen deficiency in the upwelling system off Peru. J. Mar. Res. 41:263-279.

Tunnicliffe, V., 1981. High species diversity and abundance of the epibenthic community of an oxygen deficient basin. Nature 194:354-356.

III.2 DISTRIBUTION AND RESPIRATION OF MUNIDA QUADRISPINA (BENEDICT 1902) IN SAANICH INLET, B.C.

B. Burd

INTRODUCTION

The extensive anoxia of the deep water of Saanich Inlet means that most of the silt bottom lacks animal life, and the benthic fauna is mainly cliff dwelling or epibenthic. Since the anoxic layer is unstable during flushing, established cliff fauna can be severely affected by oxygen fluctuations.

Using the submersible Pisces IV, Tunnicliffe (1981) found a high diversity and abundance in the epibenthic attached fauna of Saanich Inlet in spite of the fluctuating oxygen conditions characteristic of this fjord (Herlinveaux 1962; Anderson and Devol 1973). The present study deals with the effect of oxygen fluctuations on the distribution of a mobile species in this community, the galatheid crab Munida quadrispina (Benedict 1902). Sampling was done using Pisces IV, stationed at the Institute of Ocean Sciences, in Saanich Inlet.

A series of submersible dives made in Saanich Inlet in May 1980 revealed that M. quadrispina was the dominant mobile invertebrate on the cliff, and was present in large monospecific concentrations in severely oxygen depleted areas, with only one or two attached invertebrate species present. It was hypothesized that the distribution of M. quadrispina in oxygen depleted areas of Saanich Inlet was most profoundly affected by oxygen.

The second part of the study involved measuring the respiratory capacities of M. quadrispina, for comparison with oxygen levels at which this species lives in the field.

METHODS

Three locations at the head of Saanich Inlet were sampled. These were far from the flushing source, so that oxygen depletion was prolonged. In this

report, McCurdy Point (48°33.6'N, 123°31.5'W) will be discussed, although results were similar for all locations. Two other B.C. fjords were visited during the study, to examine M. quadrispina distributions in well oxygenated basins.

Niskin bottles were used to sample water from 20 m to 200 m at McCurdy Point. Temperature and salinity measurements were made from these samples. Dissolved oxygen analysis was done by modified Winkler titration (Strickland and Parsons 1972) from bottle casts and in the submersible using water samples obtained through an external port.

Sampling from the submersible involved taking several photographs every 5 or 10 m in depth from bottom up the cliff face, to 30 m (the upper limit of distribution of M. quadrispina). A rubber bumper arm extended out in front of the viewport, supporting a 900 cm^2 frame which was placed against the cliff and photographed to determine population density.

The deep end of a line of nine traps was weighted, with a pinger attached to the weight. The line was lowered along the cliff and tied to shore. The pinger was located from Pisces IV. Each trap along the line was thereby located and photographed. Crabs retrieved from traps were measured and preserved, or kept alive for later use. The relationships of size distribution of M. quadrispina with depth and oxygen were tested at the 1% level using regression analysis, combining all trap data collected from McCurdy Point.

Respiration experiments were done on 25 trapped crabs of various sizes. Methods used were similar to those described by Quetin and Childress (1976). Oxygen consumption was measured from 3 ml/l down to a concentration at which equilibrium was lost. This occurred just after the oxygen concentration had declined to a level at which regulation of respiration could not be maintained (Pc). The relationships of respiration rate and Pc to wet weight were tested (at the 1% level) by correlation. Carapace length was substituted for wet weight so that the relationship of carapace length vs. Pc could be compared at the 1% level by analysis of covariance with the relationship of carapace length vs. habitat oxygen concentration determined from the trap data.

RESULTS

The complete cycle of oxygen depletion and replenishment which is an annual event in Saanich Inlet (Anderson and Devol, 1973; Herlinveaux, 1962) can be clearly observed in Figure 1. Anoxia developed in April 1980 and dissipated by October 23. An influx over the sill of dense oxygenated bottom water began in August 1980, forcing the anoxic layer upwards to a midwater depth in September and dissipating anoxia by the end of October. Flushing ended before January 1981, and progressive stagnation and biological respiration resulted in a second deoxygenated layer by May 1981. Temperatures below 30 m ranged from 8.5°C to 11.0°C. Salinity was 29.5 $^{0}/_{00}$ to 31.25 $^{0}/_{00}$ in this depth range.

M. quadrispina were limited to depths at which oxygen levels were above 0.1 to 0.15 ml/l (Fig. 1). The maximum depth of M. quadrispina in these areas therefore varied from month to month in relation to the oxygen cycle. In Jervis Inlet and Howe Sound, B.C., M. quadrispina were found to the bottom of the cliff (680 m and 280 m respectively). These basins were not oxygen depleted at the time of sampling.

Maximum density of M. quadrispina always occurred within the 0.1 to 0.15 ml/l oxygen zone where there were no predator species. In September 1980 the density peak was about $50/m^2$ (Fig. 2). As the limiting oxygen layer was elevated in October, the population was compressed upwards, resulting in a density peak $>100/m^2$ for a considerable depth range. No dead animals were observed. By February 1981, after the low oxygen layer had retreated, the peak declined to about $50/m^2$ again. This compression and spreading indicates that the crabs migrate to avoid oxygen depletion.

Carapace length increased significantly as depth increased (Fig. 3). Since oxygen declined with increasing depth in Saanich Inlet, it was found that carapace length increased significantly as oxygen decreased. The correlation coefficient was higher for this relationship than for carapace length versus depth.

Regulated respiration levels and Pc(ml/l) both decreased significantly as

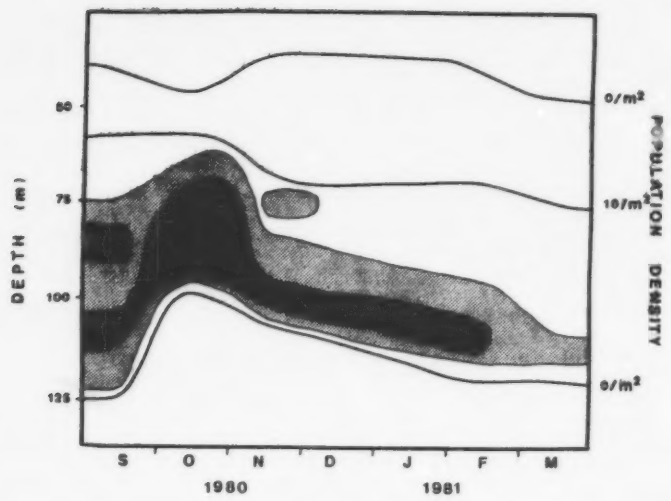

Fig. 1. Oxygen profile and depth limit (o) of M. quadrispina.

= 0 ml/l, = 0-0.1 ml/l = 0.1 to 0.15,ml/l oxygen.

wet weight increased (Fig. 4). Carapace length vs. Pc was not significantly different than carapace length versus oxygen concentration (from Fig. 3) when compared by ANCOVA.

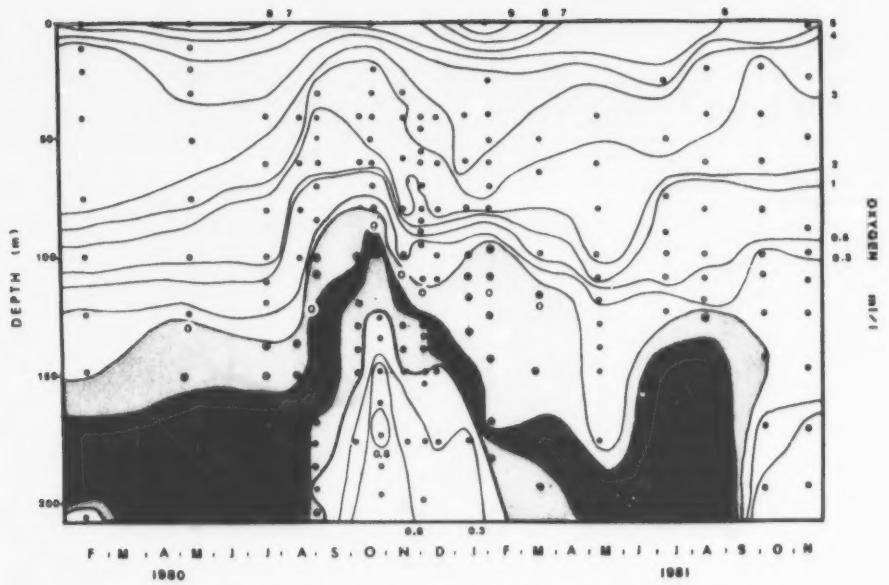

Fig. 2. Density over depth and time of M. quadrispina. Zones are <20/m^2 (white), <50/m^2, <100/m^2 and >100/m^2 (black).

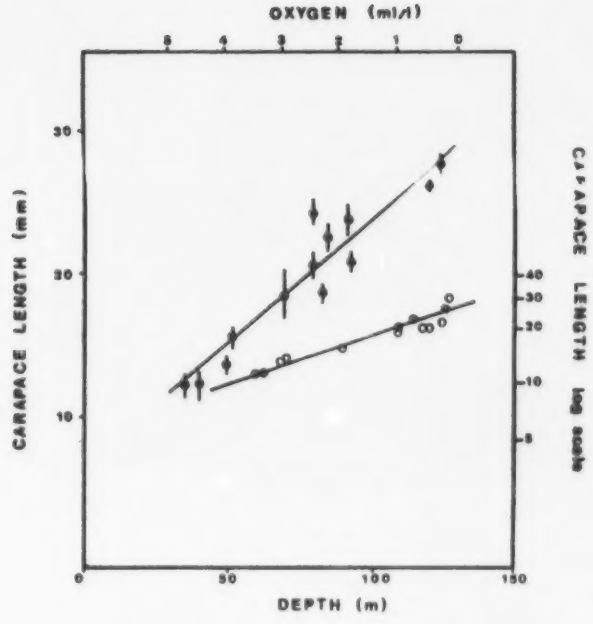

Fig. 3. Carapace length vs. depth (±standard error) and oxygen (o) in M quadrispina from combined trap data.

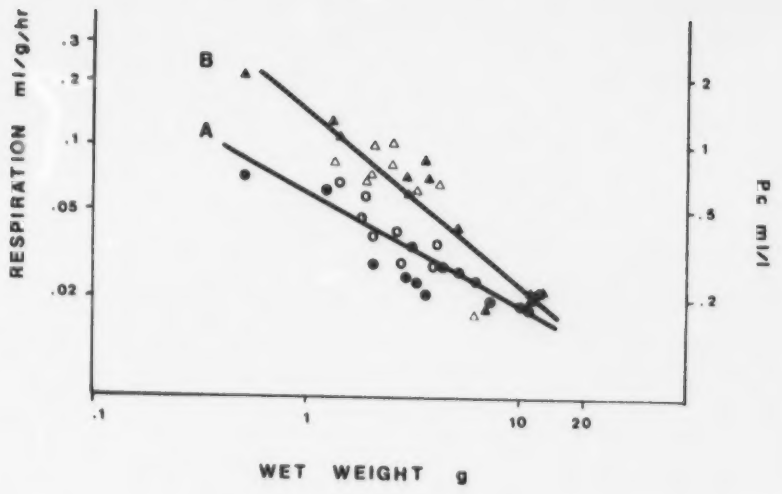

Fig. 4. Respiration (A) and Pc (B) vs. weight in M. quadrispina

DISCUSSION

Since temperature and salinity varied little during this study, oxygen was the only widely fluctuating water characteristic measured that might affect the distribution of the M. quadrispina population of Saanich Inlet.

Results of this study and Levings (1980a) study in Howe Sound indicate the M. quadrispina is well adapted to exist in severly oxygen depleted area (0.1 to 0.15 ml/l oxygen concentrations) which cannot be inhabited by most other invertebrate species. M. quadrispina density was, in fact, highest in the oxygen depleted zone. The animal was apparently able to avoid critical low oxygen levels by vertical migration.

The size distribution observed at McCurdy Point was obviously an adaptation to changes in oxygen concentration since only the largest crabs were found living at oxygen levels of 0.1 to 0.15 ml/l. This was confirmed by the close agreement between field size distributions and Pc levels measured in the lab, and suggests that Pc could possibly be used as an indicator of field oxygen tolerance in other Saanich Inlet invertebrate species.

REFERENCES

Anderson, J.J. and A.H. Devol, 1973. Deepwater renewal in Saanich Inlet, an intermittently anoxic basin. Estuar. Coast. Mar. Sci. 1:1-10.

Herlinveaux, R., 1962. Oceanography of Saanich Inlet in Vancouver Island, British Columbia. J. Fish. Res. Board Can. 19:6-26.

Levings, C.D., 1980. Demersal and benthic communities in Howe sound Basin and their responses to dissolved oxygen deficiency. Can. Tech. Rep. Fish. Aqu. Sci. 951:27 p.

Quetin, L.B. and J.J. Childress, 1976. Respiratory adaptations of Pleuroncodes planipes to its environment off Baja California. Mar. Biol. 38:327-334.

REFERENCES cont'd

Strickland, J.D.H. and T.R. Parsons, 1972. A practical handbook of seawater analysis. Fish. Res. Board Bull. 167. 309 pp.

Tunnicliffe, V., 1981. High species diversity and abundance of the epibenthic community in an oxygen deficient basin. Nature 294:354-356.

III.3 SEASONAL AND VERTICAL DISTRIBUTION OF MEDUSAE, SIPHONOPHORES AND CTENOPHORES IN SAANICH INLET

C.E. Mills

Abundance and diversity of "jellyfishes" in waters around Vancouver Island are unusally high. There are approximately 50 species of hydromedusae, 7 species of siphonophores, 4 species of scyphomedusae and 11 species of ctenophores. All of these species are predators on zooplankton, taking crustaceans and/or gelatinous forms as prey.

Between 1976 and 1983 I carried out a series of collections and experiments to define the seasonal and vertical distributions and vertical migration regimes of the jellyfish population, and to determine some of the mechanisms responsible for the specific locations in the water column occupied by the various species. The work was done in Saanich Inlet and at the Friday Harbor Laboratories (F.H.L.) in the San Juan Islands. Most of the information is available in my dissertation (Mills 1982) and has been or will be published in similar form in refereed journals.

Between 1976 and 1980 an extensive year-round series of observations and collections of jellyfishes was made from the F.H.L. floating dock (Mills 1981a). Seasonal distributions and relative abundances of 60+ species have been tabulated from these data; the seasonal patterns repeat annually although population sizes vary from year to year. The seasonal information is accompanied by an annotated species list including notes on life history, times of sexual maturity, and polyp distribution. Dichotomous taxonomic keys are provided for the identification on hydromedusae, siphonophores, scyphomedusae and ctenophores (Appendix in Mills 1982).

A 2-year series of closing net plankton tows (1977-1979) at the University of Victoria "Station E" in Saanich Inlet complemented the above study with quantitative information on vertical distribution of jellyfish. Over 600 replicate vertical tows were taken biweekly or monthly (on 65 dates), using a 333 um, 3/4 m diameter closing net to sample intervals of 1-25 m, 25-50 m, 50-75 m, 75-130 m, and 130-180 m. The jellyfish species assemblage

of Saanich Inlet is approximately the same as at F.H.L. Although fewer jellyfish were obtained in the Saanich Inlet plankton tows than were seen from the F.H.L. dock, vertical distribution has been well established for many species from these plankton tows; 11 species are discussed and figured in the dissertation. The plankton samples included nine 24- or 48-hour series of tows whose purpose was to elucidate which species of jellyfish undergo vertical migrations within the broad limits of the sampling intervals. Vertical migration data is also figured for the above 11 species.

Direct observation of the distributions of plankton organisms was made possible by use of the submersible Pisces IV. In conjunction with Prof. G.O. Mackie, 40 daytime dives in Saanich Inlet have been made during August 1980, November 1980, March 1981, April 1981, August 1982, October 1982, November 1982; an additional 10 dives are scheduled for March 1983 and May 1983. A night dive has been included in almost every diving series. During all dives we have visually estimated, using a nearest-neighbor approach, the quantitative distribution of all macrozooplankton (larger than copepods) continuously throughout the water column. The observations from the 1980-1981 dives are thoroughly documented in Chapter 4 of my dissertation. The 1982-1983 dives have not yet been written up. Direct observation from the Pisces IV was especially useful in realizing fine details of vertical distributions, calculating real population densities, and observing behaviour of undisturbed deep water medusae and ctenophores in situ. Precise vertical stratification and near-isolation of different taxa was found to be characteristic of Saanich Inlet during most dives and could not have been identified or predicated on the basis of plankton net samples.

Laboratory experiments were undertaken in which vertical migration of medusae was generated in a 2 m tall (1500 l) transparent tank. Manipulation of the light regime revealed the vertical migration behaviours to be light-dependent rather than circadian in origin for the species of jellyfish studied. Vertical migration patterns of various medusa species in the tank corresponded to known vertical migration patterns of those species in the field. Tank observations also revealed that different species of medusae have characteristic swimming and feeding patterns that apparently served to divide food resources in the sea. Most jellyfish are negatively buoyant and

their species-specific swimming patterns provide a mechanism for maintaining vertical position as well as for feeding.

Ionic and osmotic regulation of buoyancy with respect to vertical migration have also been investigated in the laboratory. The hypothesis that vertical migration of jellyfish might be facilitated by diel variation in a known ionic epithelial transport system (i.e. exclusion of sulphate ion from the mesogloeal fluid) has been ruled out by experiments using radioactive sulphate and atomic absorption spectrophotometry of various cations. It is concluded that vertical migration of medusae and ctenophores is accomplished by swimming. Dynamic changes in buoyancy may, however, result when jellyfish experience varying salinities. Manipulation of salinities between 19 and 38$^{o}/_{oo}$ shows jellyfish to be osmoconformers over this range of salinities. The density of the mesogloeal fluid varies with the density of the surrounding sea water. Osmotic adjustment over this salinity range can take up to several hours. Prior to regaining their equilibrium buoyancies, jellyfish sink when introduced to low salinity water and float in high salinity water. Hence, simple density differences combined with the natural intermittent swimming behaviour of most medusae suggest that in many cases medusae may not actually be able to cross sudden density gradients such as might occur at thermoclines or pycnoclines. However, in the event that a jellyfish is moved into water of a different salinity, its ability to adjust will allow the animal to resume normal swimming and feeding activities within a short time.

REFERENCES

Mills, C.E., 1981a. Seasonal occurrence of planktonic medusae and ctenophores in the San Juan Archipelago (NE Pacific). Wasmann Journal of Biology 39:6-29.

Mills, C.E., 1981b. Diversity of swimming behaviors in hydromedusae as related to feeding and utilization of space. Mar. Biol. 39: 185-189.

Mills, C.E., 1982. Patterns and mechanisms of vertical distribution of medusae and ctenophores. Ph.D. Dissertation, Department of Biology, University of Victoria, Victoria, B.C., 384 pp.

III.4 SUBMERSIBLE OBSERVATIONS OF PLANKTON DISTRIBUTION IN SAANICH INLET

G.O. Mackie

Direct observation of the plankton from the submersible has several advantages. It allows the animals' normal behavior to be studied: feeding, locomotion, escape responses, bioluminescence, color changes, etc. Delicate forms which are poorly preserved in net samples (particularly certain ctenophores) can be studied and counted. Their distribution can be determined with greater precision than is normally possible with net sampling. Unexpectedly narrow bands of plankton have repeatedly been observed in which densities greatly surpassed previous estimates. Comparisions of plankton stratification can be rapidly made at different locations and in day-night sequences. Night dives have revealed patterns of vertical migration.

200 kHz SONAR side scans have been carried out concurrently with Pisces dives. Amphipods, euphausiids and crab larvae (Munida) are probably responsible for most of the scattering. These forms cannot be distinquished from one another on the basis of their appearance in the scans except where the distribution of one or other was sufficiently distinctive to make identification feasible. Two species of copepods, stage V, Neocalanus plumchrus and Calanus pacifica have been identified in the scans on occasions when they were present at high densities (ca. 50,000.m^{-3}) while overwintering within narrow belts at 130 m and 90 m respectively. Copepods give very fine grain scatter patterns compared with larger crustaceans. It is suggested that side scan SONAR offers advantages over surface echosounding for resolutions of small planktonic forms.

These studies were carried out with the cooperation of C. Mills and others (submersible work) and J. Wilson (side scan SONAR)

The complete text of the submersible study is presented in Mackie, G.O., and C.E. Mills 1983. Use of the Pisces IV submersible for zooplankton studies in coastal waters of British Columbia. Can. J. Fish. Aquat. Sciences. 40:763-776.

III.5 UNDERWATER BIRDWATCHING

W.C. Austin

THE PROBLEM

The inability to identify many larger organisms *in situ* from visual cues has been a limiting factor in assessing subSCUBA epifaunal composition in British Columbia waters (Anderson 1978MS; LeBlond and Sibert 1973; Tunnicliffe pers. comm.). Some groups with representatives which are conspicuous in size and numbers have in the past received little attention from systematists locally (e.g., Porifera, Anthozoa, Ascidiacea). This is reflected in the high percentage of new records during recent surveys (Austin *et al*. 1982MS; Austin 1983MS; Tunnicliffe pers. comm.).

Representatives of other groups which are better known locally, have only been described from preserved material. Such material may, of course, differ considerably from life in form and colour. Other characters commonly employed as diagnostic are microscopic or internal, and hence not available for remote visual identification. However, characters such as form in life, behaviour, habitat, and associated species *may* be diagnostic. But until such characters are assessed for at least a number of taxa within each group their diagnostic value is suspect. Bird field identification is perhaps the best example of the effective use of characters which can be seen from a distance and are considered diagnostic at the species level. The situation is much less satisfactory for the underwater observer.

A PROPOSAL

Submersibles, remote control vehicles, film and video cameras are being increasingly used by government, university and private groups to record information in the Canadian Pacific Ocean. An effective *in situ* identification program would enchance the quality of data interpretation by these groups. Over the past two years the author working with V. Tunnicliffe has identified approximately 150 invertebrate species observed from the submersible Pisces IV (operated by the Institute of Ocean Sciences). Freshly

collected samples were generally taken to confirm initial identifications. In many cases characters not previously employed were assessed for diagnostic value.

A search of the literature for the northeast Pacific indicated that between 50 and 2000 metres there are at least 500 species (350 invertebrates, 150 vertebrates) which might be identifiable to the species level from remote visual cues. The identification program proposed for these species consists of five components:

1. Data base requirements
2. Tabular keys
3. Photographic data set
4. Mnemonic descriptors
5. Reference collection

DATA BASE REQUIREMENTS

The types and quality of visual records have been reviewed elsewhere (e.g., Anderson 1978MS; Hersey 1967). They include colour vs. black and white; colour temperature accuracy; flat vs. stereoscopic image; still vs. moving image; vertical, oblique or horizontal aspect; image resolution; and image proximity. The image types necessary for adequate diagnosis should be considered for each taxonomic group. For example, black and white still photographs may be adequate for identification of box crabs but not sea anemones in local waters; vertical images may be satisfactory for brittle stars but not for sea pens.

TABULAR KEYS

Given that at present the diagnostic value of remotely visible characters may be suspect, and that in many groups there is a likelihood that numbers of unrecorded species occur in local waters, all available clues should be utilized in the identification process. Also, when an unknown cannot be identified to species there is more information content in stating which species it may be and which it is not than in simply calling it a member of family x or genus y.

A tabular key format was designed with the above considerations in mind (Fig. 1). Although tabular in form these keys are not patterned after those described by Newell (1970, 1977). Species known or suspected to occur in local waters are listed on the horizontal axis (abbreviated names) while potential characters and other data sources are listed vertically. Statements which are true for the unknown sample may be circled or otherwise identified. The columns are then scanned vertically for best fit and inconsistencies noted. Statements which are false might also be crossed out or otherwise signified to positively exclude certain species from consideration. The system can be used manually (e.g., using water soluble ink on keys printed on plastic) or computerized. The keys are artificial and hierarchal with two to three levels from phylum to species level. Characters can be amended without rebuilding the keys. A pictorial glossary accompanies each key set. Microscopic or internal characters may be included where useful in the event that specimens are in hand.

PHOTOGRAPHIC DATA SET

A set of high quality colour photographs would accompany the tabular keys. These would, of course, be limited to the availability of living material. The procedure to date has been to take colour photographs in situ; and, where possible, to collect a specimen for subsequent close-up photographs in shipboard aquaria. Species of similar appearance would be grouped together for ease in scanning. Examples are included in the oral presentation of this paper.

MNEMONIC DESCRIPTORS

A checklist of species will be annotated with abbreviated descriptions of visible characters. These will be for the purpose of aiding recall rather than for positive identification.

REFERENCE COLLECTION

A reference collection of included species should be available to serve

In Situ Identification Program — Khoyatan

TABULAR KEY 6: Pennatulacea

	Koph hisp	Unbe lind	Anth gran	Funi park	Hali rigi	Dist verr	Scle spec	Stac supe	Acan albu	Balt call	Balt sept	Styl colu	Styl elon	Virg brom	Virg "tube"	Virg "glac"	Penn "phos"	Ptil gurn
Suppl. information																		
Voucher	+	+	-	-	-	-	-	-	-	+	+	-	+	+		+	+	+
Figure	+	+	+	+	+	+	-	+	+	+	+	+	+	+	+	+	+	+
Colour photo	-	-	-	-	-	-	-	-	-	-	+	-	-	-	+?	-	+	+
Reference no.(simulated)	1225	134	276	276	381	385	443	443	127	227	231	231	274	274	338	339	440	119
Distribution ( )=unpub																		
B.C./Wash.	(X)	(X)								(X)	X	X	X		X?	(X)	X	X
CCal/Oreg;NOT BC/Wash			X	X	X		X	X	X					X				
SAlask; NOT BC/Wash																		
SCal; not above						X												
Bathymetry (meters)																		
min. over range	1080	152	85		1000	1300	1000	54	75	130	20	24	18	710			110	10
min. Cal-Alask	1800	600	860	750	1830	1800	(109)	54	75	450	20	24	18	710	20	207	110	10
max. known	2800	5300	2800	1150	5000	2800	4300	950	110	2000	200?		100	1100			2100	130
Substrate																		
soft (mud,sand)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Colour alive	?	?	?	?	?	red yel	?	?	?	purp brwn	wht	?	wht		?	?	prp◊red	org◊
Size (decimeters)	1	5	5	5	2	5	1	2-3	2	10◊	25◊	2	3	1	2	?	1	4
Overall form																		
club shaped	X◊+																	
stalked bell		X◊+																
wide,straight(L/W<10:1)									X						X		X◊+	X◊+
narr,straight(L/W>15:1)			X	X		X◊+	X	X		X	X	X	X	X		X		
narr,curved					X◊+													
Polyp organization																		
free at apex	X	X																
free, scattered			X	X														
free bilateral					X	X	X?	X										
on bilateral spines					X◊+	X◊+												
leaves; <v=stalk width										X	X	X	X	X	X	X		
on leaves;2+Xs stalk W									X								X	X
Approx. polyp size																		
> 5 mm	30◊	50◊	20◊	8			5											
<v= 2 mm					X	X		X	X	X	X	X	X	X	X	X	X	X
No. polyps/cluster																		
non clustered			X	X	X	X	X											
3-6 at apex	X◊+																	
9-11 at apex		X◊+																
4 free/cluster								X◊										
3-6/leaf									X	X				X	X			
9+/leaf											X	X	X			X	X	X
Microscopic chars.																		
no./polyps/row								4		2-5	12-15	20-24	15-17	3-6	3-6	3-6	nos.	nos
spicules in polyps	+	-	-	+			+	+	+	+	±			-	-	-	+	+
spicule under polyps	-	-	-	-	+	+		+			±	+	+◊+	-	-	-		

Koph	Unbe	Anth	Funi	Hali	Dist	Scle	Stac	Acan	Balt	Balt	Styl	Styl	Virg	Virg	Virg	Penn	Ptil
hisp	lind	gran	park	rigi	verr	gran	supe	albu	call	sept	colu	elon	brom	tube	glac	phos	gurn

Fig. 1. An example of a tabular key for *in situ* identification of deep water epifauna.

both as vouchers for the keys and photographs developed in this program, and as a source of information for those using the program.

HEXACTINELLIDS, AN EXAMPLE IN SAANICH INLET

IN SITU IDENTIFICATION

Hexactinellid sponges are a major component of the epilithic fauna in Saanich Inlet as well as in a number of other fjords in local waters (e.g., G. Silver pers. comm.; Tunnicliffe 1982, pers. observ.). Until recently four species were recorded from British Columbia. Primarily as a result of submersible operations there are now twelve known species including six within one family (Austin 1983MS). Diagnostic characters in the literature for separating species in this family have been almost exclusively limited to microscopic features. Observations on populations of living representatives have yielded data on colour, size, form, habitat and depth which, while still not entirely satisfactory, have been of considerable aid in separating species at the macroscopic level.

ECOLOGICAL IMPLICATIONS

Sponges in this family, the Rossellidae, show a vertical zonation pattern including one species regularly occurring as shallow as 15 metres. Only in the Antarctic region are sponges recorded in comparably shallow waters (Dayton et al. 1974; Kirkpatrick 1907; Koltun 1970) although they might be predicted to occur in shallow water in some other regions. The upper bathymetric limit of these sponges from offshore into fjord systems in British Columbia appears from limited data to be correlated with silicate concentrations. Data for silicate levels is drawn from Hill et al. (1980), Lucas (1929), MacDonald et al. (1983), Stephens et al. (1967), and Tully and Dodimead (1957). High silicate levels occur in shallow water around the Antarctic as well (e.g., Littlepage 1965). Silicate levels may decrease rapidly above the upper limit of hexactinellids during periods of diatom blooms (e.g., Stephens et al. 1967). Silicate requirements of diatoms during frustule growth are well known (Officer and Rhyther 1980; Paasche 1973; Sullivan and Volcani 1981; Werner 1977). Similar requirements by hexatinellids can be inferred from their high

silicate content, approximately 85% of the dry weight in preliminary analyses on a local species. This suggests that, at least during certain periods, shallow water hexactinellids may compete with diatoms for available silicates. Given appropriate assessment of other factors, the upper bathymetric limits of hexactinellids in Saanich and in other fjords might be used as indicators of some minimal level of diatom production over time, that is as silicometers.

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REFERENCES

Anderson, E.P., 1978. Identification and enumeration of animals in benthic photographs. Dobrocky Seatech. 77 pp. Prepared for the Institute of Ocean Sciences, Sidney, B.C.

Austin, W.C., M.V. Preker, M.A. Bergey, S. Leader, 1982. Species list for invertebrates recorded from the Barkley Sound region. Bamfield Marine Station Report. 48 pp.

Austin, W.C., 1983MS. An annotated checklist of marine invertebrates in the cold temperate northeast Pacific. Khoyatan, 621 pp.

Dayton, P.K., G.A. Robilliard, R.T. Paine and L.B. Dayton, 1974. Biological accommodation in the benthic community at McMurdo Sound, Antarctica. Ecol. Monogr. 44:105-128.

Hersey, J.B. (ed.). 1967. Deep-sea photography. John Hopkins Press, Baltimore, 310 pp.

Hill, S., K. Denman, D. Mackas, and H. Sefton, 1982. Ocean ecology data report: Coastal waters off southwest Vancouver Island. Spring and Summer 1980. Can. Data Rep. Hydrogr. Ocean Sci. No. 4:103 pp.

REFERENCES cont'd

Kirkpatrick, R., 1907. Porifera. Nat. Antarctic Exped. 1901-1904. Vol. 3, 25 pp.

Koltun, V.M., 1970. Sponges of the arctic and antarctic; a faunistic review. Symp. Zool. Soc. Lond. No. 25:285-297.

Leblond, P H. and J. Sibert, 1973. Observations of large unidentified marine-animals in British Columbia and adjacent waters. Institute of Oceanography, University of B.C. MS Rep. No.28.

Littlepage, J.L., 1965. Oceanographic investigations in McMurdo Sound Antarctic. Antarct. Res. Ser., NAS, 5:1-37.

Lucas, C.C., 1929. Further oceanographic studies of the sea adjacent to the Fraser River mouth. Trans. Roy. Soc. Can., Ser. V, 23:29-58.

MacDonald, R.W., W.J. Cretney, C.S. Wong and P. Erickson, 1983. Chemical Characteristics of water in the Kitimat Fjord system. Can. Tech. Rep. Hydrogr. Ocean Sci. (in press).

Officer, C.B. and J.H. Ryther, 1980. The possible importance of silicon in marine eutropication. Mar. Ecol. Prog. Ser. 3:83-91.

Newell, I.M., 1970. Construction and use of tabular keys. Pacific Insects, 12:25-37.

Newell, I.M., 1977. Construction and use of tabular keys: addendum. Syst. Zool. 25:243-250.

Paasche, E., 1973. Silicon and ecology of marine plankton diatoms. I. *Thalassiosira pseudonana* (*Cyclotella nana*) grown in a chemostat with silicate as limiting nutrient. Mar. Biol. 19:117-126.

REFERENCES cont'd

Stephens, K., J.D. Fulton, O.D. Kennedy, A.K. Pease, 1967. Biological, chemical and physical observations Saanich Inlet, Vancouver Island, British Columbia. Fish. Res. Bd. MS Rep. Ser. No. 912, 119 pp.

Stockner, J.G., D.D. Cliff, K.R.S. Shortreed, 1979. Phytoplankton ecology of the Strait of Georgia, British Columbia. J. Fish. Res. Bd. Can. 36:657-666.

Sullivan, C.W. and B.E. Volcani, 1981. Silicon in the cellular metabolism of diatoms. In: Silicon and siliceous structures in biological systems. T.L. Simpson and B.E. Volcani, (eds.). Springer, NY, p.15-42.

Tully, J.P. and A.J. Dodimead, 1957. Properties of the water in the Strait of Georgia, British Columbia, and influencing factors. J. Fish. Res. Bd., 14:241-319.

Tunnicliffe, V., 1981. The deep-water epibenthic community of an oxygen deficient basin. Nature 294:354-356.

Werner, D., 1977. Silicate metabolism. In: The biology of diatoms. D. Werner, (ed.). Univ. Calif. Press, Berkeley.

IV. PROVISIONAL BIBLIOGRAPHY OF OCEANOGRAPHIC INFORMATION FOR SAANICH INLET

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A. PAPERS AND REPORTS

PHYSICAL

Anderson, J.J., and A.H. Devol, 1973. Deep water renewal in Saanich Inlet, an intermittently anoxic basin. Estuarine Coastal Mar. Sci. 1:1-10.

Carter, N.M., 1932. The oceanography of the fjords of southern British Columbia. Fish. Res. Bd. Can., Prog. Rep. 12: p. 7-11.

_____, 1934. The physiography and oceanography of some British Columbia fjords. 5th Pacific Sci. Cong. (Nat. Res. Counc. Can.) Proc., Vol. 1:721-733.

Herlinveaux, R.H., 1962. Oceanography of Saanich Inlet in Vancouver Island, British Columbia. J. Fish. Res. Bd. Can. 19:1-37.

_____, 1968. Features of water movement over the "sill" of Saanich Inlet, June-July 1966. Fish. Res. Bd. Can. Tech. Rep. 99. 49 pp.

_____, 1972. Oceanographic features of Saanich Inlet, 9 May-2 July 1968. Fish. Res. Bd. Can. Tech. Rep. 300. 53 pp.

Pickard, G.L., 1975. Annual and longer term variations of deepwater properties in the coastal waters of southern British Columbia. J. Fish. Res. Bd. Can. 32:1561-1587.

BIOLOGICAL

Bary, B. McK., 1966. Back scattering at 12 kc/s in relation to biomass and numbers of zooplankton organisms in Saanich Inlet, British Columbia. Deep Sea Res. 13:655-666.

REFERENCES Biological cont'd

Devol, A.H., 1981. Vertical distribution of zooplankton respiration in relation to the intense oxygen minimum zones in two British Columbia fjords. J. Plankton Res. 3:593-602.

Herlinveaux, R.H., B.W. Bary and W.E. Barraclough, 1962. Scattering of underwater sound in Saanich Inlet, British Columbia. Nature 194:36-37.

Hobson, L.A., 1980. Phytoplankton biology of Saanich Inlet, B.C. Pages 423-427 In: Fjord Oceanography. H.J. Freeland et al.(eds.). Plenum Press, N.Y. 715 pp.

Hobson, L.A., 1981. Seasonal variations in maximum photosynthetic rates of phytoplankton in Saanich Inlet, Vancouver Island, British Columbia. J. Exp. Mar. Biol. Ecol. 52:1-13.

_____, 1983. Phytoplankton crops, bacterial metabolism and oxygen in Saanich Inlet, a fjord in Vancouver Island, British Columbia. Sediment. Geol. 36:117-130.

_____ and F.A. Hartley, 1983. Ultraviolet irradiance and primary production in a Vancouver Island fjord, British Columbia, Canada. J. Plankton Res. 5:325-331.

Huntley, M.E., and L.A. Hobson, 1978. Medusa predation and plankton dynamics in a temperate fjord, British Columbia. J. Fish. Res. Bd. Can. 35:257-261.

Hutchinson, A.H., and C.C. Lucas, 1931. Epithalassa of the Strait of Georgia. Can. J. Res. 5:231-284.

_____, C.C. Lucas and M. McPhail, 1929. Seasonal variations in the chemical and physical properties of the water of the Strait of Georgia in relation to phytoplankton. Trans. Roy. Soc. Can. 3rd Series, 23:177-183.

REFERENCES cont'd

CHEMICAL AND GEOLOGICAL

Tunnicliffe, V.L., 1981. High species diversity and abundance of the epi-benthic community in an oxygen deficient basin. Nature 294:354-356.

Berrang, P.G., 1972. The effect of manganese oxide scavenging on the distribution and sedimentation of molybdenum in Saanich Inlet, British Columbia. Unpubl. M.Sc. thesis, Univ. British Columbia, Vancouver.

_____ and E.V. Grill, 1974. The effect of manganese oxide scavenging on molybdenum in Saanich Inlet, British Columbia. Mar. Chem. 2:125-148.

Broenkow, W.W., 1969. The distributions of nonconservative solutes related to the decomposition of organic material in anoxic marine basins. Unpubl. Ph.D. thesis, Univ. Washington, Seattle.

Brown, F.S., M.J. Baedecker, A. Nissenbaum and I.R. Kaplan, 1972. Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia - III. Changes in organic constituents of sediment. Geochim. Cosmochim. Acta 36:1185-1203.

Buddemeier, R.W., 1969. A radiocarbon study of the varved marine sediments of Saanich Inlet, British Columbia. Unpubl. Ph.D. thesis, Univ. Washington, Seattle.

Clapp, C.H., 1913. Geology of the Victoria and Saanich Map Areas, Vancouver Island, B.C. Geol. Survey, Dept. of Mines and Tech. Surveys, Ottawa.

Cranston, R.E., 1980. Cr. Species in Saanich and Jervis Inlets. Pages 689-692 In: Fjord Oceanography. H.J. Freeland et al. (eds.). Plenum Press, New York, N.Y.

REFERENCES Chemical and Biological cont'd

Gross, M.G., 1967. Concentrations of minor elements in diatomaceous sediments of a stagnant fjord. Pages 273-282 In: Estuaries. G.H. Lauff (ed.). Am. Assoc. Advan. Sci. Publ. 83.

_____, S.M. Gucluer, J.S. Creager and W.A. Dawson, 1963. Varved marine sediments in a stagnant fjord. Science 141:918-919.

Gucluer, S.M., 1962. Recent sediment in Saanich Inlet, British Columbia. Unpubl. M.Sc. thesis, Univ. Washington, Seattle.

_____ and M.G. Gross, 1964. Recent marine sediments in Saanich Inlet, a stagnant marine basin. Limnol. Oceanogr. 9:359-376.

Hyndman, R.D., 1976. Heat flow measurements in the inlets of southwestern British Columbia. J. Geophys. Res. 81:337-349.

Kolodny, Y., 1969. Studies in geochemistry of uranium and phosphorites. Unpubl. Ph.D. thesis, Univ. California, Los Angeles.

_____, and I.R. Kaplan, 1973. Deposition of uranium in the sediment and interstitial water of an anoxic fjord. Pages 418-442 In: Symposium on Hydrogeochemistry and Biogeochemistry, Vol. 1. Clarke Co., Washington, D.C.

Kvenvolden, K.A., E. Peterson and F.S. Brown, 1970. Racemization of amino acids in sediments from Saanich Inlet, British Columbia. Science 169: 1079-1082.

Lilley, M.D., J.A. Baross and L.I. Gordon, 1982. Dissolved hydrogen and methane in Saanich Inlet, British Columbia. Deep Sea Res. 29:1471-1484.

Lister, C.R.B., 1967. Shallow seismic profiling in Saanich Inlet. Northwest Sci. 41:80-83.

REFERENCES Chemical and Biological cont'd

Mathews, W.H., and J.W. Murray, 1966. Recent sediments and their environment of deposition, Strait of Georgia and Fraser River Delta (a manual for field conferences). Tenneco Oil and Minerals, Calgary.

Murray, J.W., V. Grundmanis and Wm. Smethie Jr., 1978. Interstitial water-chemistry in the sediments of Saanich Inlet. Geochim. Gosmochim. Acta. 42: 1011-1026.

Nissenbaum, A., 1974. Deuterium content of humic acids from marine and non-marine environments. Mar. Chem. 2: 59-63.

_____, M.J. Baedecker and I.R. Kaplan, 1972. Studies on dissolved organic matter from interstitial water of a reducing marine fjord. Pages 427-440 In: Organic Geochemistry, 1971. H.R. von Gaertner and H. Wehner (eds.). Pergamon Press, Oxford.

_____ and I.R. Kaplan, 1972. Chemical and isotopic evidence for the in situ origin of marine humic substances. Limnol. Oceanogr. 17: 570-582.

_____, B.J. Presley and I.R. Kaplan, 1972. Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia - I. Chemical and isotopic changes in major components of interstitial water. Geochim. Cosmochim. Acta 36: 1007-1027.

Peterson, D.H., 1967. Fatty acid composition of certain shallow-water marine sediments. Unpubl. Ph.D. thesis, Univ. Washington, Seattle.

Presley, B.J., 1969. Chemistry of interstitial water from marine sediments. Unpubl. Ph.D. thesis, Univ. California, Los Angeles.

_____, Y. Kolodny, A. Nissenbaum and I.R. Kaplan, 1972. Early diagenesis in a reducing fjord, Saanich Inlet, British Columbia - II. Trace element distribution in interstitial water and sediment. Geochim. Cosmochim. Acta 36: 1073-1090.

REFERENCES cont'd

Richards, F.A., 1965. Anoxic basins and fjords. Pages 611-645 In: Chemical Oceanography, Vol. 1. J.P. Riley and G. Skirrow (eds.). Academic Press, London.

Roberts, R.W., 1974. Marine sedimentological data of the inland waters of Washington State (Strait of Juan de Fuca and Puget Sound). Univ. Wash. Dep. Oceanogr. Spec. Rep. 56.

Waldichuk, M., 1968. Waste disposal in relation to the physical environment-oceanographic aspects. Syesis 1:4-27.

Yang, A.I.C., 1971. Variations of natural radiocarbon during the last 11 millenia and geophysical mechanisms for producing them. Unpubl. Ph.D. thesis, Univ. Washington, Seattle.

_____ and A.W. Fairhall, 1972. Variations of natural radiocarbon during the last 11 millenia and geophysical mechanisms for producing them. 8th Int. Radiocarbon Dating Conf. (Roy. Soc. N.Z.). Proc., Vol. 1: A44-A57.

B. DATA SETS

Barraclough, W.E., and R.H. Herlinveaux, 1961. Midwater trawling through the echo scattering layer in Saanich Inlet, March 1-2, 1961. Fish. Res. Bd. Can. MS Rep. B, No. 712.

_____ and R.H. Herlinveaux, 1965. Exploratory studies of the echo scattering layers in Saanich Inlet and the Strait of Georgia, B.C. Fish. Res. Bd. Can. MS Rep. (Oceanogr. Limnol.) 199. 42 pp.

_____ and J.D. Fulton, 1968. Data Record. Food of larval and juvenile fish caught with a surface trawl in Saanich Inlet during June and July 1966. Fish. Res. Bd. Can. MS Rep. 1003. 78 pp.

REFERENCES cont'd

_____, D.G. Robinson and J.D. Fulton, 1968. Data record. Number, size composition, weight, and food of larval and juvenile fish caught with a two-boat surface trawl in Saanich Inlet, April 23-July 21, 1968. Fish Res. Bd. Can. MS Rep. 1004. 305 pp.

Bishop, S.O., J.D. Fulton, O.D. Kennedy and K. Stephens, 1966. Data record. Physical chemical and biological data, Strait of Georgia, March to October, 1965. Fish. Res. Bd. Can. MS Rep. (Oceanogr. Limnol.) 211. 171 pp. (p. 67-71, 106, 119, 141-2, 158, 160, 162, 164, 166).*

Coastal Zone Oceanography Section, 1980. Salinity/Temperature Profiles in Saanich Inlet, B.C. Part I: April 1976-December 1977. Pac. Mar. Sci. Rep. 80-5(1), p. 1-172. Part II: 1978. Pac. Mar. Sci. Rep. 80-5(2), p. 194-387. Institute of Ocean Sciences, Sidney, B.C.

Devol, Allan H. 1977, Chemical and Physical Observations in Saanich Inlet, 1961-1975. Univ. Wash. Dep. Oceanogr. Spec. Rep. 64. 153 pp.

Fulton, J.D., O.D. Kennedy, K. Stephens and J. Skelding, 1967. Data Record. Physical, chemical and biological data, Strait of Georgia, 1966. Fish. Res. Bd. Can. MS Rep. 915. 145 pp. (p. 27, 39, 50, 62, 72, 84, 94-97, 101, 103, 105, 107, 109, 112, 121, 123, 126, 128, 130, 133, 139, 141-143, 145).

_____, O.D. Kennedy, H. Seki and K. Stephens, 1969. Biological, chemical and physical observations in Saanich Inlet, Vancouver Island, British Columbia, 1968. Fish. Res. Bd. Can. MS Rep. 1018. 109 pp.

---

* For each report (where necessary), pages listed within brackets contain data dealing <u>specifically</u> with Saanich Inlet.

REFERENCES cont'd

Herlinveaux, R.H., O.D Kennedy and H.J. Hollister, 1960. Oceanographic data record, Coastal-Seaways Project, November 16 to December 11, 1959. Fish. Res. Bd. Can. MS Rep. (Oceanogr. Limnol.) 58. 134 pp. (p. 13-17, 111-112, 123-134).

_____, 1966-67. Unpublished Data. Oceanographic features of Cowichan Bay - surface movements, and temperature and salinity distributions. On file at the Ocean Information Division, Institute of Ocean Sciences, Sidney, B.C.

_____, 1980. Unpublished data. Temperature, salinity, surface currents, biological inventory, etc. On file at the Ocean Information Division, Institute of Ocean Sciences, Sidney, B.C.

Institute of Oceanography, University of British Columbia, Vancouver, B.C. Data Reports.*

No. 4, 1955. C.G.M.V. "Cancolim II" Survey of British Columbia Coast, 1953, 72 pp. (p. 64-69).

No. 5, 1955. Saanich Inlet Cruises, 1954, 1955. 26 pp.

No. 19, 1962. British Columbia Inlet Cruises, 1961. 62 pp. (p. 24-25, 54).

No. 21, 1963. British Columbia Inlet Cruises, 1962. 90 pp. (p. 2-6, 53-60, 84-88).

No. 23, 1964. British Columbia Inlet Cruises, 1963. 102 pp. (p. 9-13, 25-28, 39-42, 62, 82-85).

---

* The Institute of Oceanography at the University of British Columbia was reestablished as the Department of Oceanography on 1 April, 1979. Data reports prepared subsequent to that date have been published by the Department; however, the numerical sequence begun previously has been retained.

REFERENCES cont'd

No. 25, 1966. British Columbia and Alaska Inlet Cruises, 1965. 39 pp. (p. 13-15, 36-39).

No. 26, 1967. British Columbia and Alaska Inlets and Pacific Cruises, 1966. 40 pp. (p. 11-16, 36-40).

No. 27, 1968. British Columbia Inlet Cruises, 1967. 36 pp. (p. 3-4, 22, 36).

No. 28, 1969. British Columbia Inlet Cruises, 1968. 59 pp. (p. 4-5, 12-13, 33-35, 50-52, 56).

No. 30, 1970. British Columbia Inlets and Pacific Cruises, 1969. 65 pp. (p. 3-4, 20, 42-44, 50-51, 56-57, 60-61).

No. 32, 1971. British Columbia Inlets and Pacific Cruises, 1970. 58 pp. (p. 2-3, 9, 55-56, 58).

No. 33, 1972. British Columbia Inlets and Pacific Cruises, 1971. 68 pp. (p. 2, 16, 20, 26, 46, 49, 52-54, 58, 65, 67).

No. 34, 1973. British Columbia Inlets and Pacific Cruises, 1972. 95 pp. plus Appendix (1). (p. 6-7, 17-19, 55-56, 87-88).

No. 35, 1974. British Columbia Inlets Cruises, 1973. 127 pp. (p. 14-15, 51-52, 74-75, 89, 110).

No. 37, 1975. British Columbia Inlets Cruises, 1974. 106 pp. (p. 1-2, 27-30, 61-62, 71, 80).

No. 48, 1981. British Columbia Inlet Cruises, 1980. 45 pp. (p. 5, 14).

No. 50, 1982. British Columbia Inlets Cruises, 1981. 53 pp. (p. 15).

REFERENCES cont'd

No. 51, 1983. British Columbia Inlet Cruises, 1982. 43 pp. (p. 7-8, 22-23).

No. 52, 1984. British Columbia Inlets Cruises, 1983. 25 pp. (p. 7-8, 12-14).

Juniper, S.K., 1983. Unpublished data. Temperature and salinity (CTD), dissolved oxygen, H_2S, bacterial activity, photographs of wall fauna (from Pisces IV). On file at the Ocean Ecology Division, Institute of Ocean Sciences, Sidney, B.C.

Lane, R.K., R.H. Herlinveaux, W.R. Harling and H.J. Hollister, 1960. Oceanographic data record, Coastal and Seaways Projects, October 3 to 26, 1960. Fish. Res. Bd. Can. MS Rep.(Oceanogr. Limnol.) 83. 142 pp.-(p.101).

Pacific Oceanographic Group, 1959. Physical and chemical data record, Coastal Seaways Project, March 31 to April 22, 1959. Fish. Res. Bd. Can. MS Rept. (Oceanogr. Limnol.) 47. 170 pp. (p.11-15, 155-156).

_____, 1959. Oceanographic data record, Coastal-Seaways Project, June 8 to July 1, 1959. Fish. Res. Bd. Can. MS Rep. (Oceanogr. Limnol.) 52. 210 pp. (p. 11-17, 157-158, 173-183).

_____, 1952, 1954, 1959, 1961 and 1963. Unpublished data. Temperature and Salinity. On file at the Ocean Information Division, Institute of Ocean Sciences, Sidney, B.C.

Stephens, K., J.D. Fulton, O.D. Kennedy and A.K. Pease, 1967. Biological, chemical and physical observations in Saanich Inlet, Vancouver Island, British Columbia. Fish. Res. Bd. Can. MS Rep. 912. 119 pp.

Tunnicliffe, V.L., 1980-82. Unpublished data. Temperature, salinity, dissolved oxygen. On file at the Ocean Ecology Division, Institute of Ocean Sciences, Sidney, B.C.

REFERENCES cont'd

Whitney, F.A., 1979-82. Unpublished data. Temperature, salinity, hydrogen sulfide, sedimentation rates, organic carbon, production rates (phyto-plankton, bacteria). On file at the Ocean Chemistry Division, Institute of Ocean Sciences, Sidney, B.C.

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POOR

QUALITY

ORIGINAL